

Computer Networks

Chapter 5 Link Layer

Adapted from Book Slides: “Computer Networking: A Top-Down Approach”

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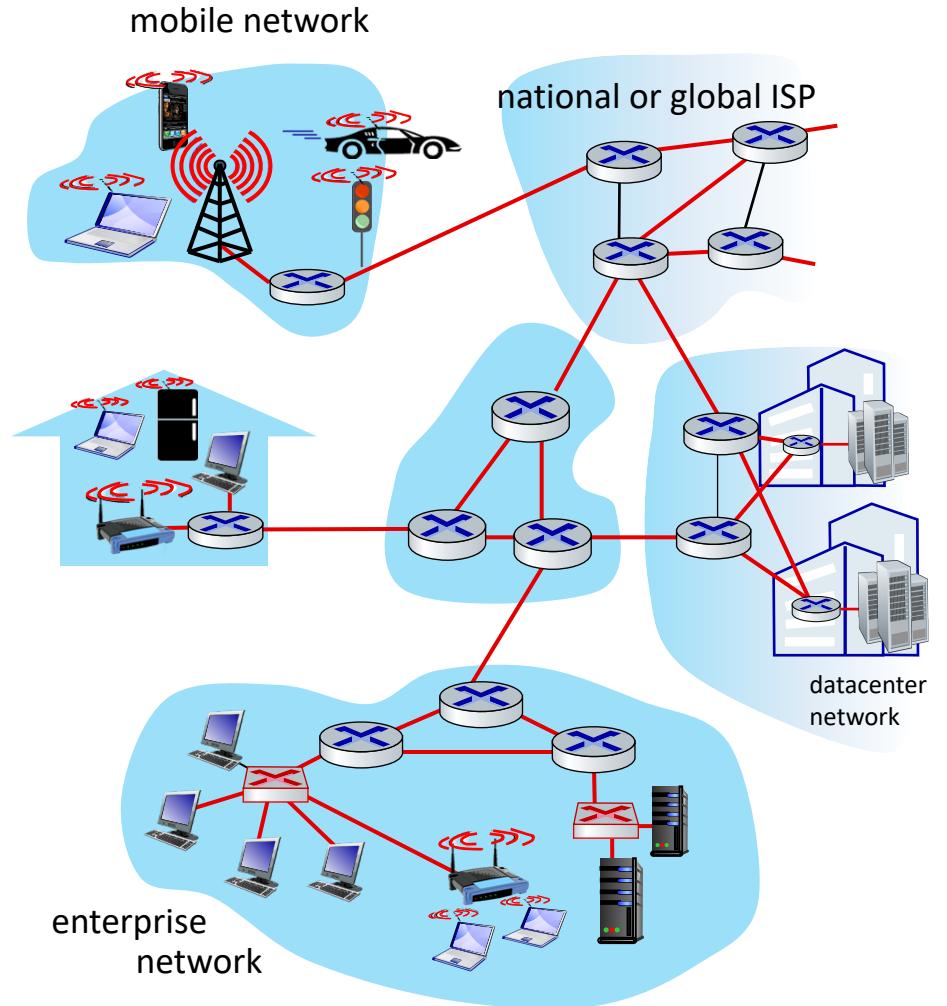
Chapter 5: our goals

- understand principles behind link layer services:
 - error detection, correction
 - sharing a broadcast channel: multiple access
 - link layer addressing
 - local area networks:
 - Ethernet
- datacenter networks

Chapter 5: roadmap

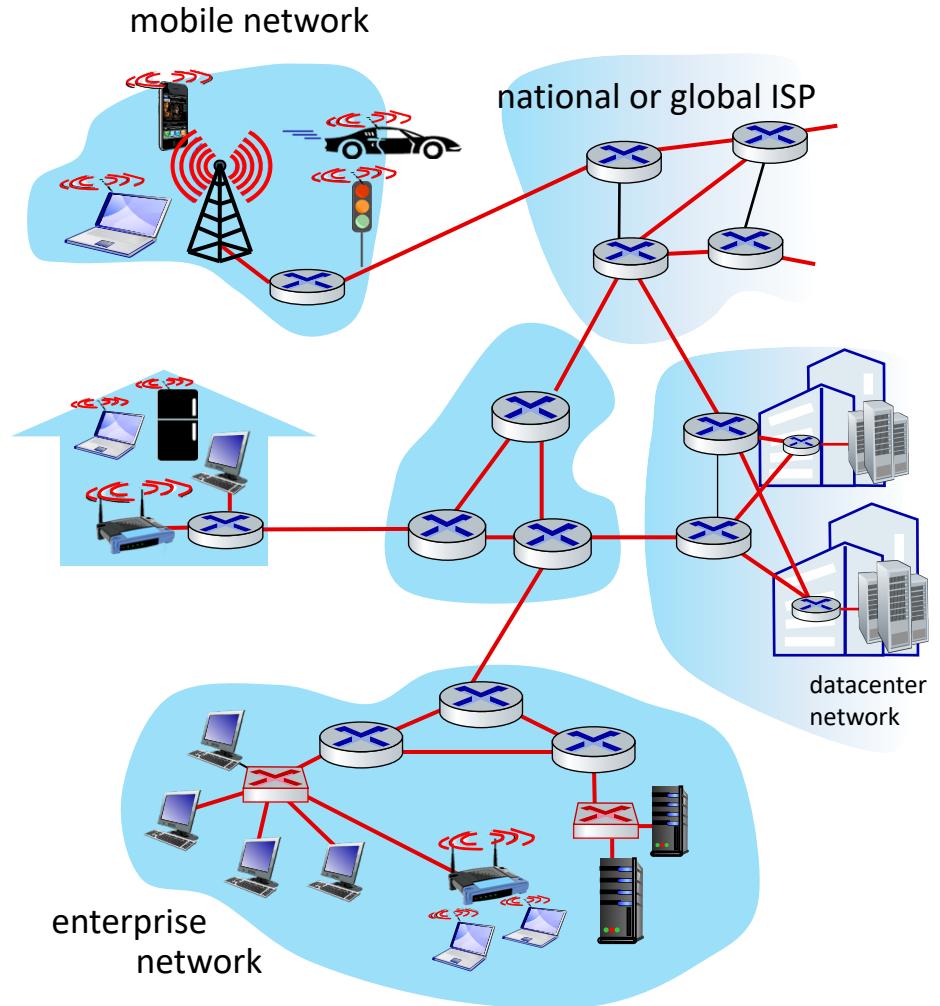
- introduction
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Link layer: introduction



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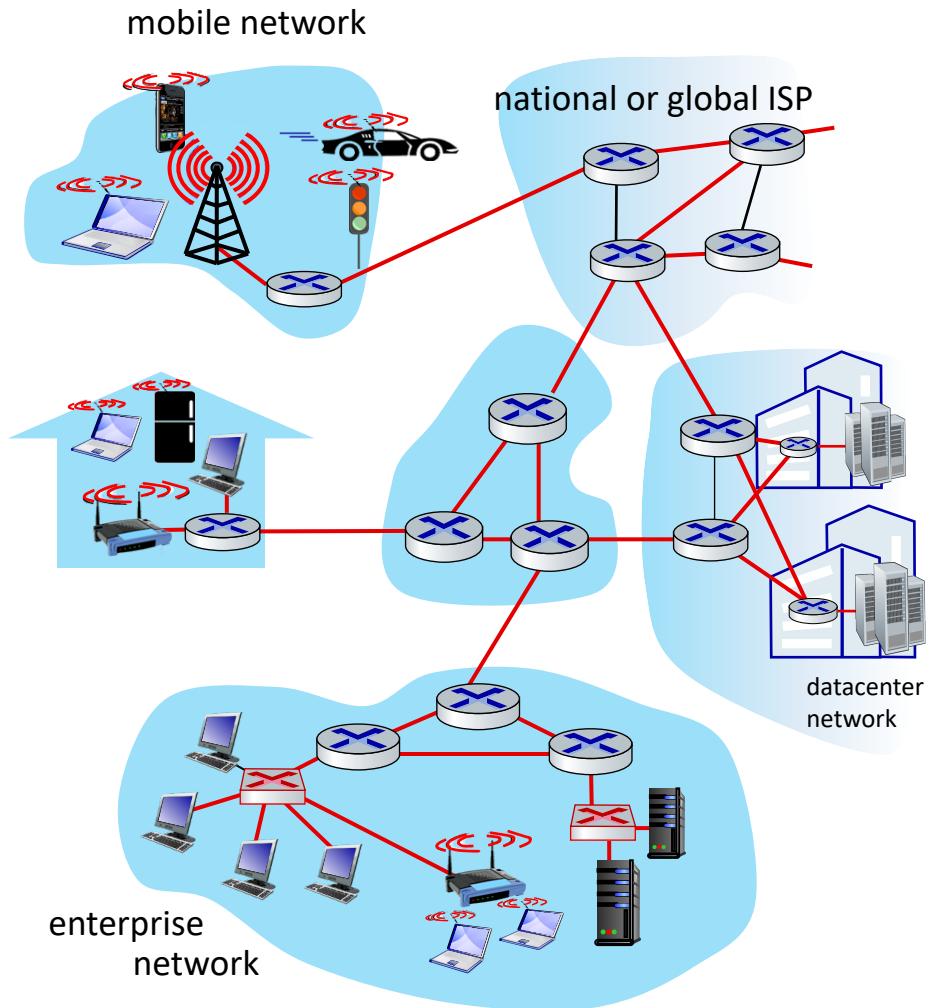
terminology:



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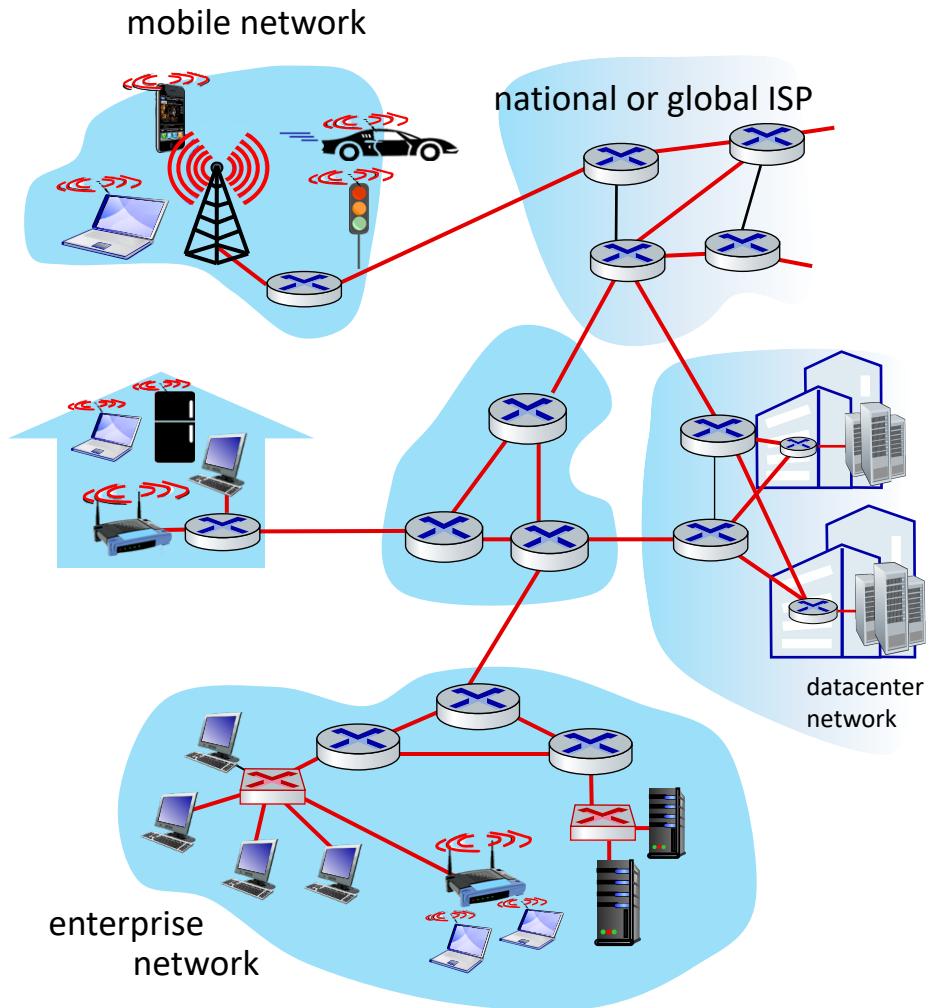
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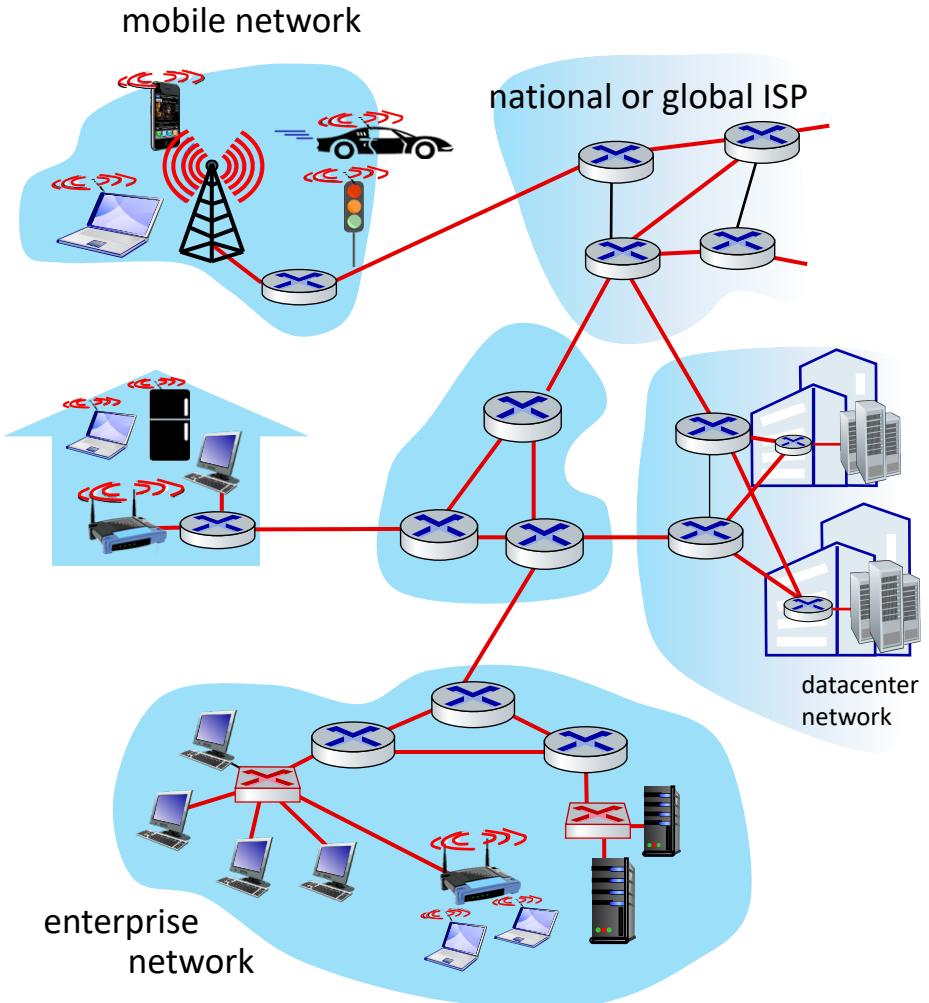
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- communication channels that connect adjacent nodes along communication path: links



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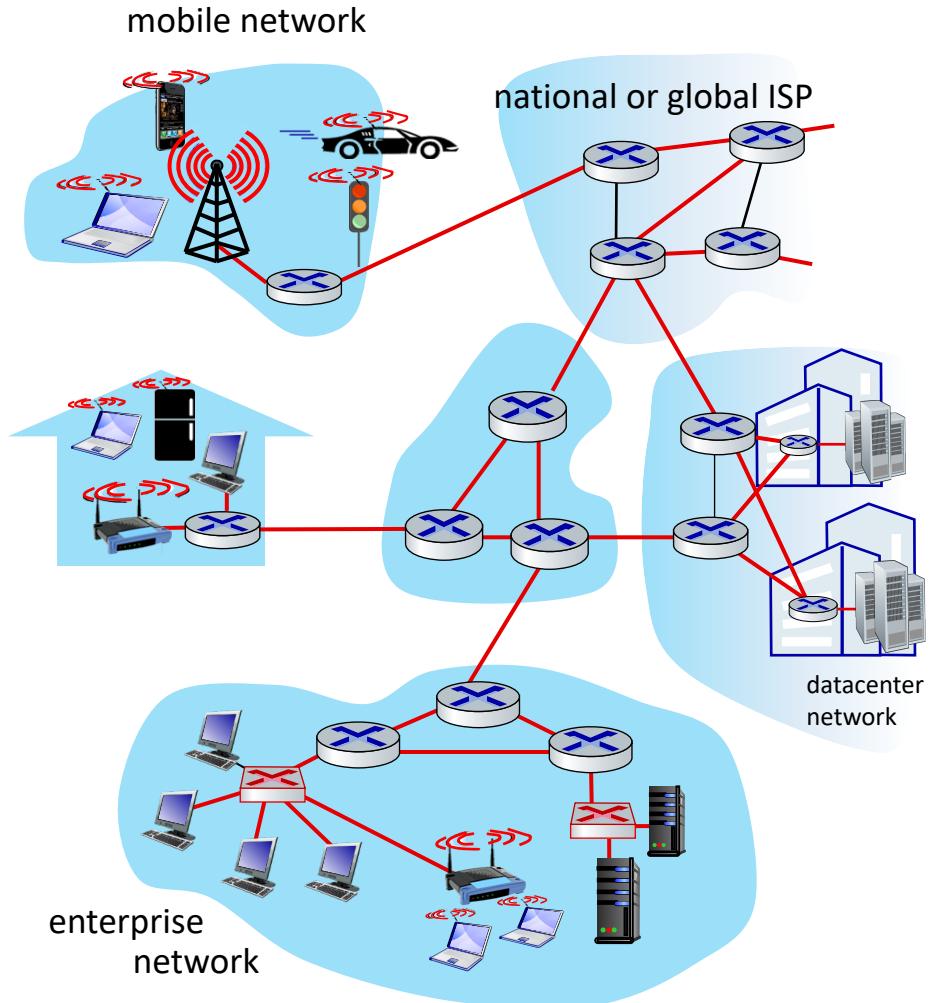
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 - wired



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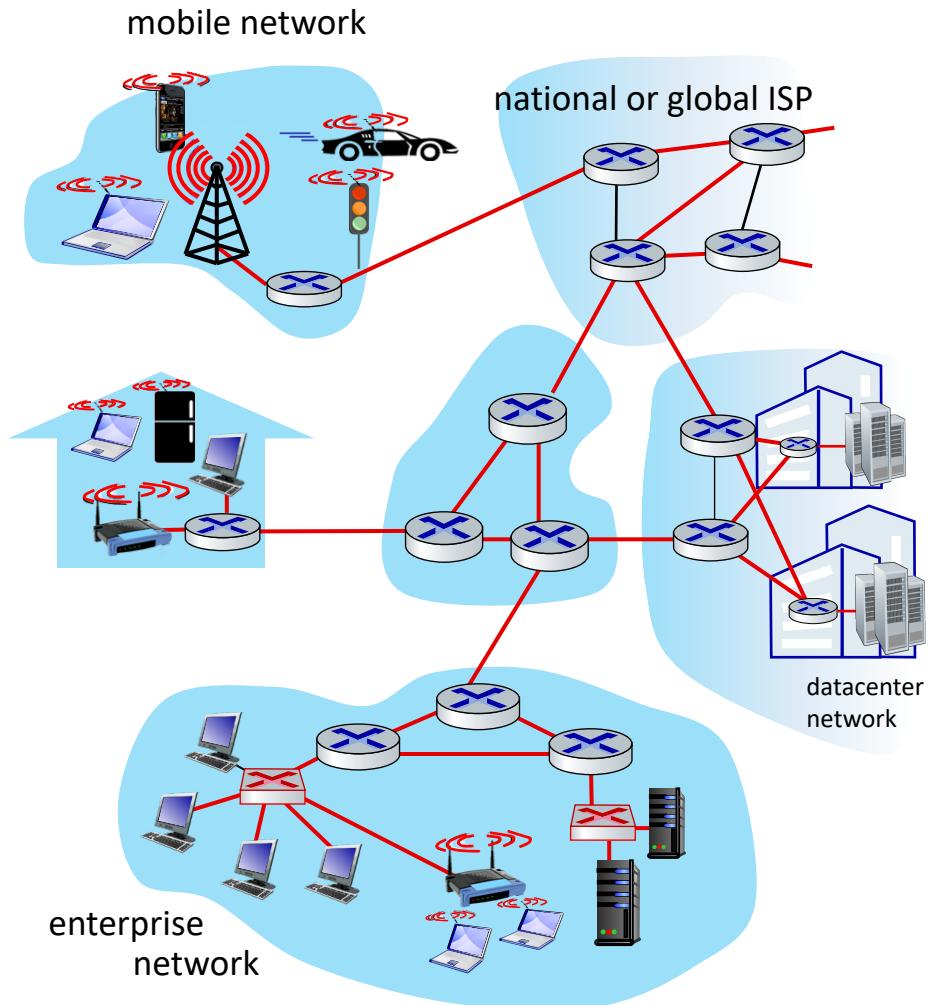
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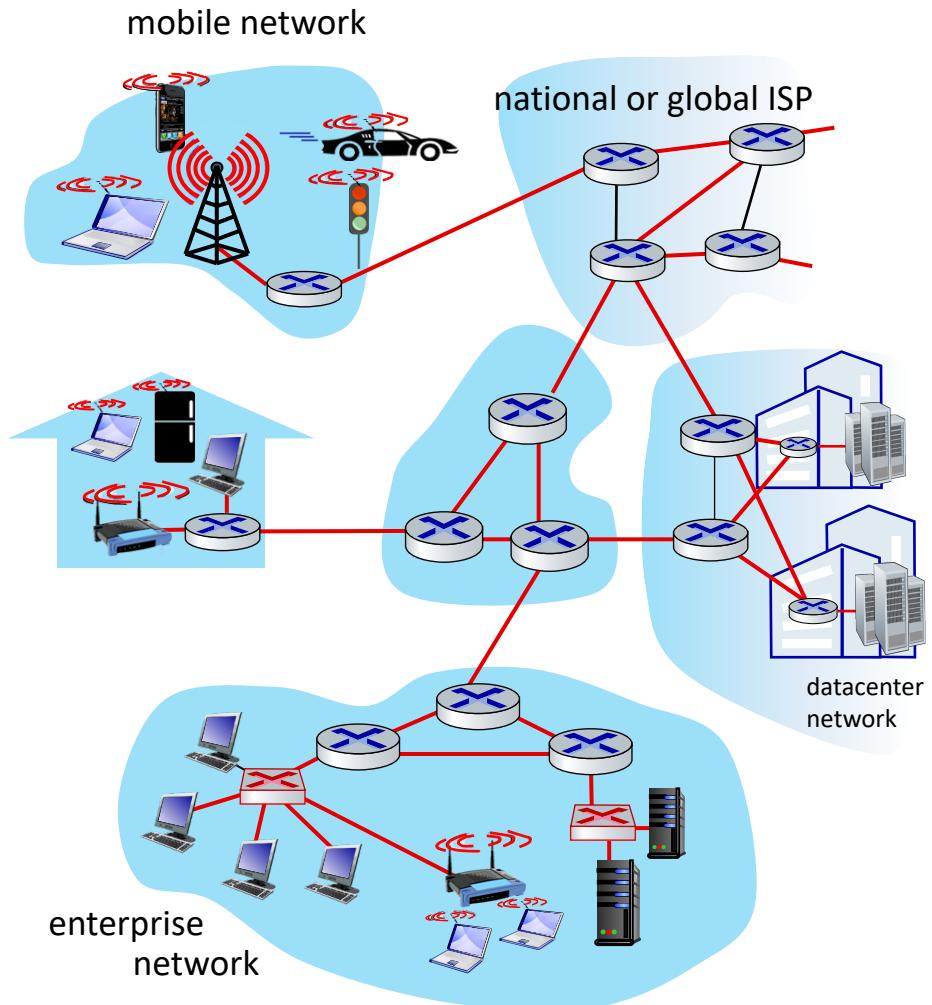
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- layer-2 packet: *frame*, encapsulates datagram

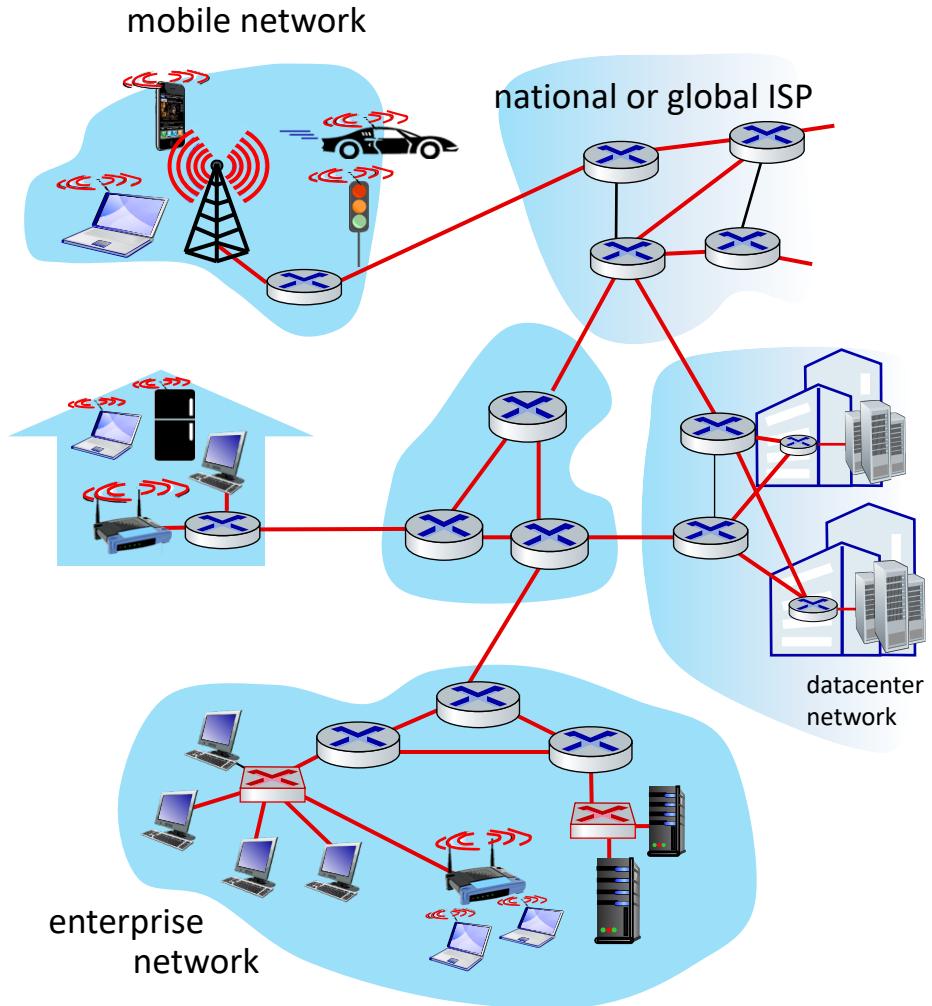


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link layer has responsibility of transferring datagram from one node to physically adjacent node over a link



Link layer: context

- datagram transferred by different link protocols over different links:
 - e.g., WiFi on first link, Ethernet on next link
- each link protocol provides different services
 - e.g., may or may not provide reliable data transfer over link

transportation analogy:

- trip from Princeton to Lausanne
 - limo: Princeton to JFK
 - plane: JFK to Geneva
 - train: Geneva to Lausanne
- tourist = **datagram**
- transport segment = **communication link**
- transportation mode = **link-layer protocol**
- travel agent = **routing algorithm**

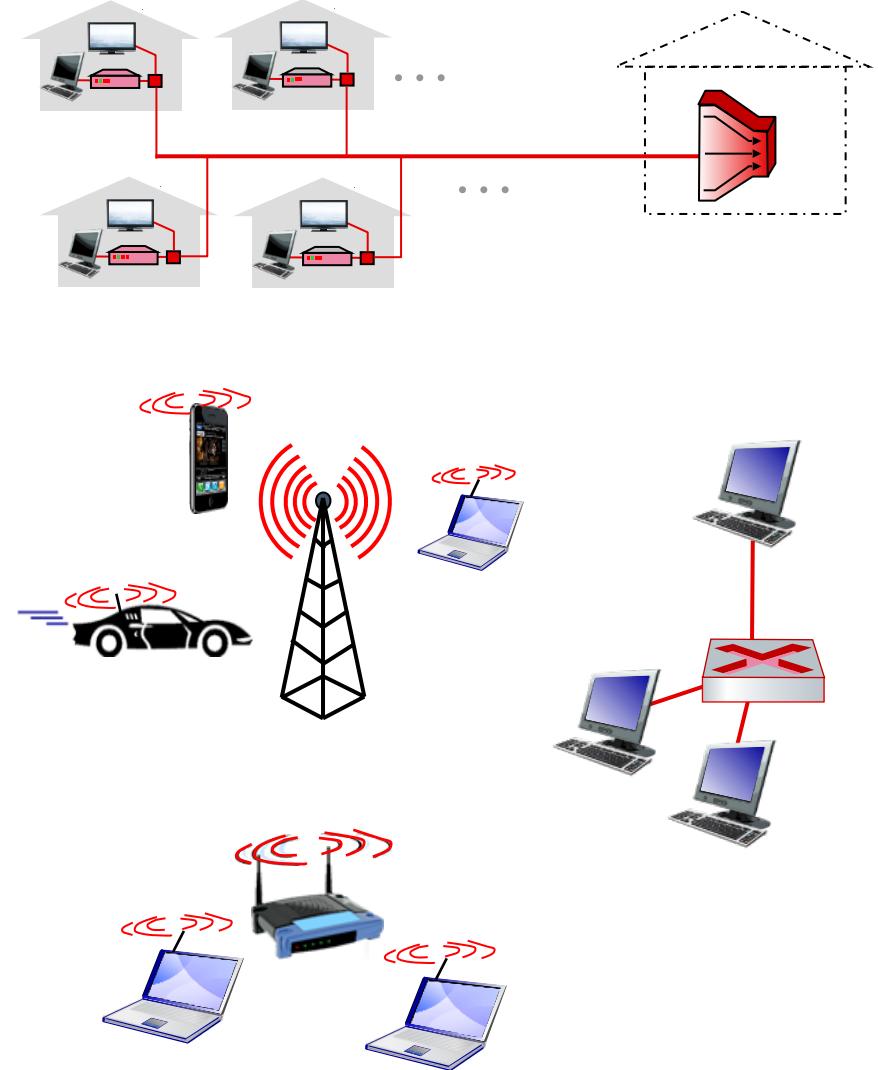
Link layer: services

- **framing, link access:**

- encapsulate datagram into frame, adding header, trailer
- channel access if shared medium
- “MAC” addresses in frame headers identify source, destination
 - different from IP address!

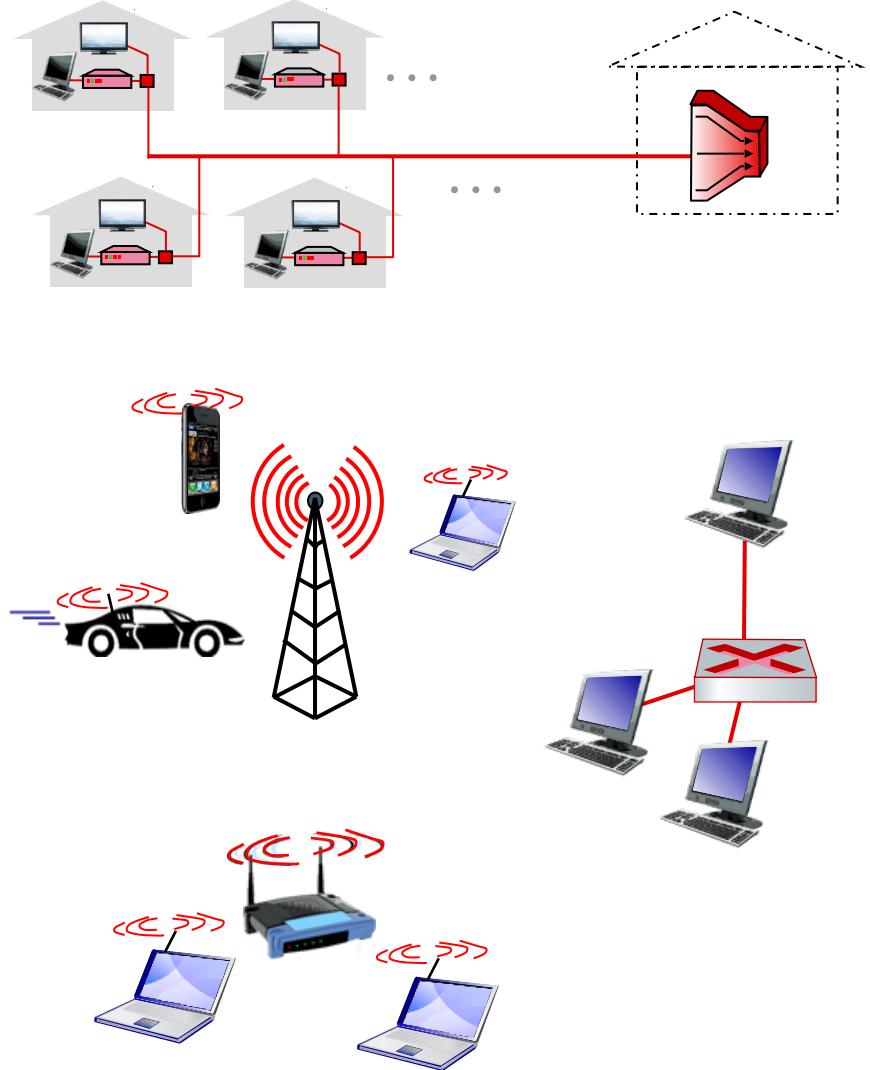
- **reliable delivery between adjacent nodes**

- we already know how to do this (chapter 3)!
- seldom used on low bit-error links (fiber, some twisted pair)
- wireless links: high error rates
 - Q: why both link-level and end-end reliability?



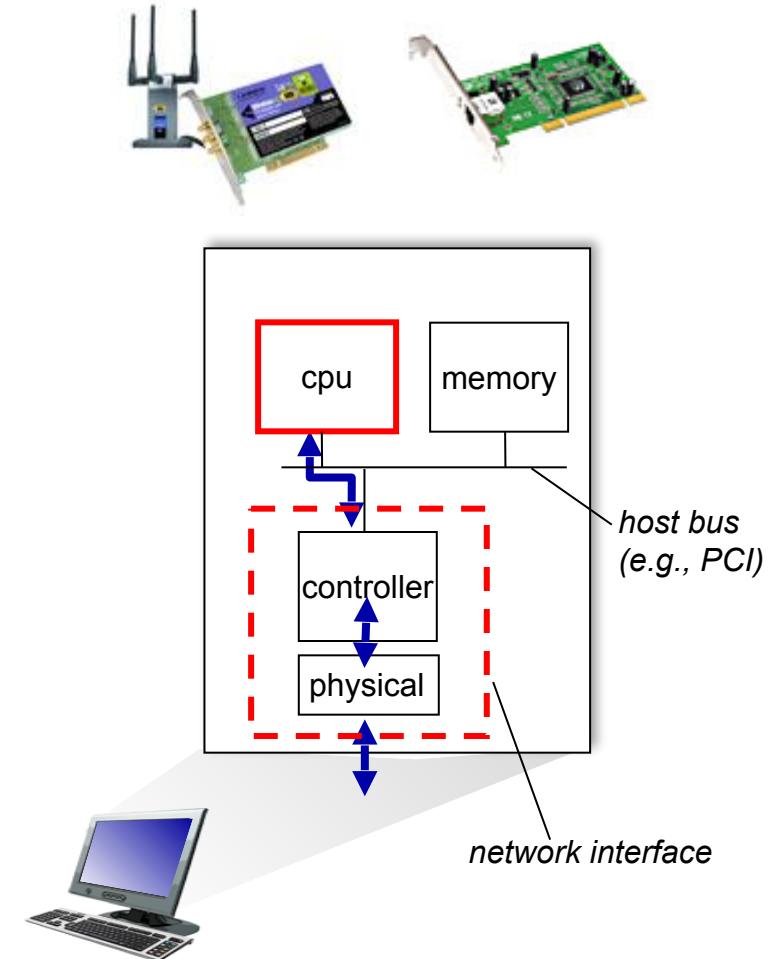
Link layer: services (more)

- **flow control:**
 - pacing between adjacent sending and receiving nodes
- **error detection:**
 - errors caused by signal attenuation, noise
 - receiver detects errors:
 - signals retransmission, or drops frame
- **error correction:**
 - receiver identifies *and corrects* bit error(s) without retransmission
- **half-duplex and full-duplex:**
 - with half duplex, nodes at both ends of link can transmit, but not at same time



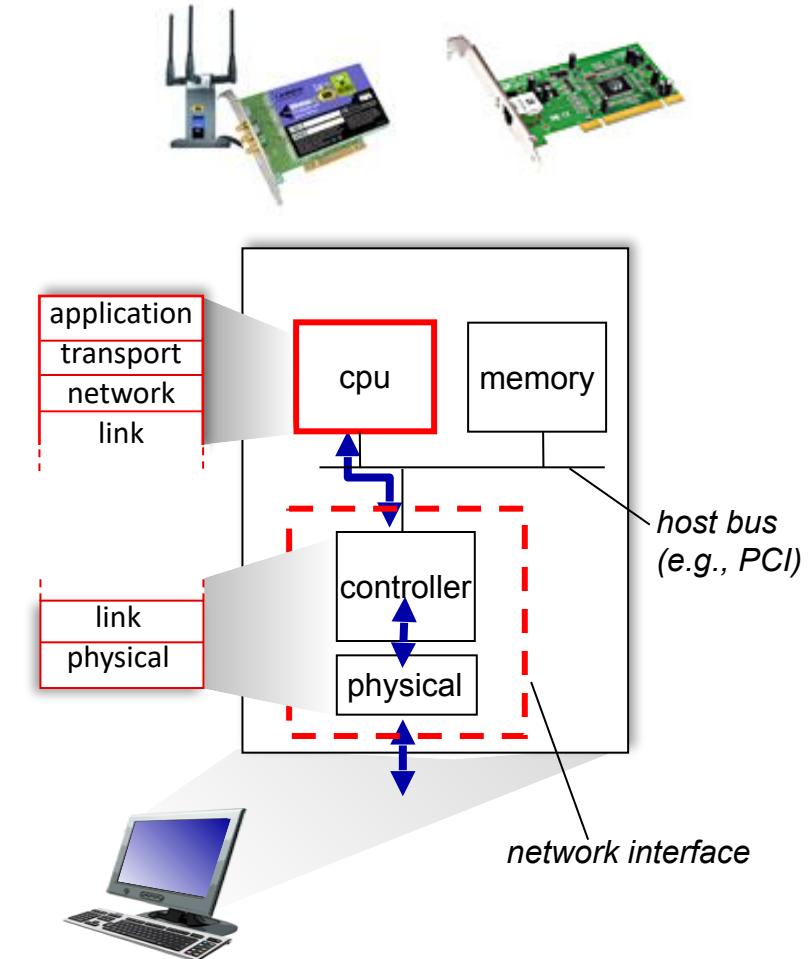
Where is the link layer implemented?

- in each-and-every host
- link layer implemented in *network interface card* (NIC) or on a chip
 - Ethernet, WiFi card or chip
 - implements link, physical layer
- attaches into host's system buses
- combination of hardware, software, firmware

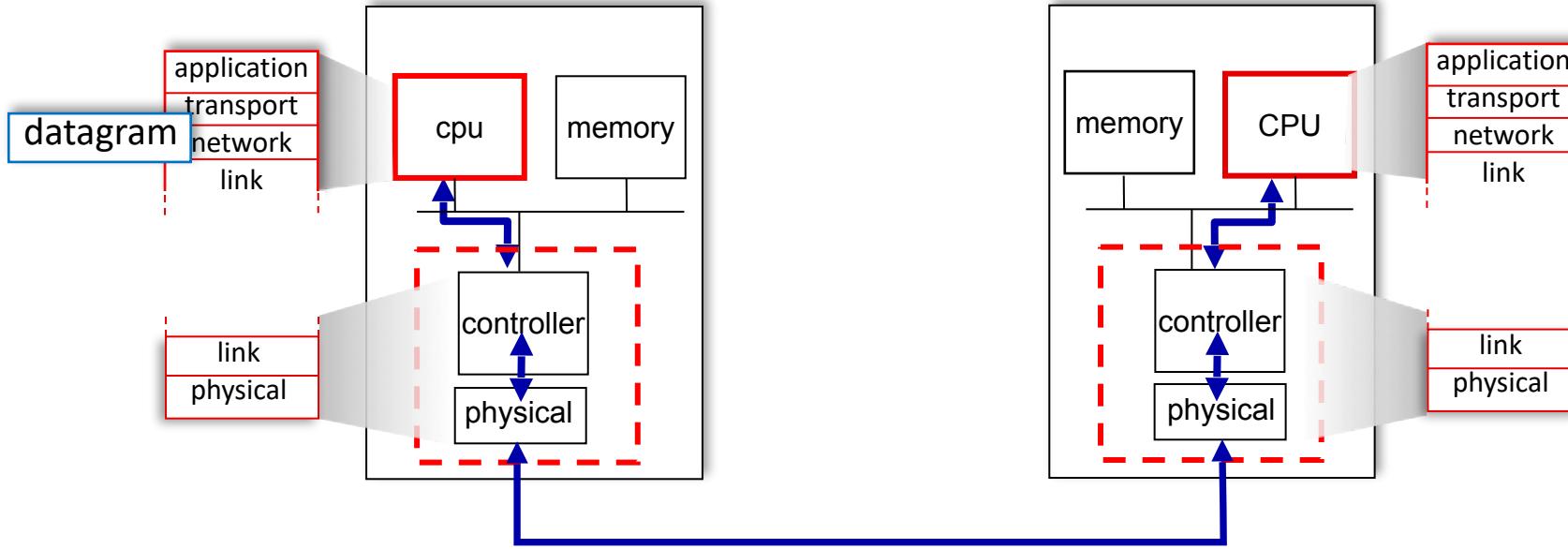


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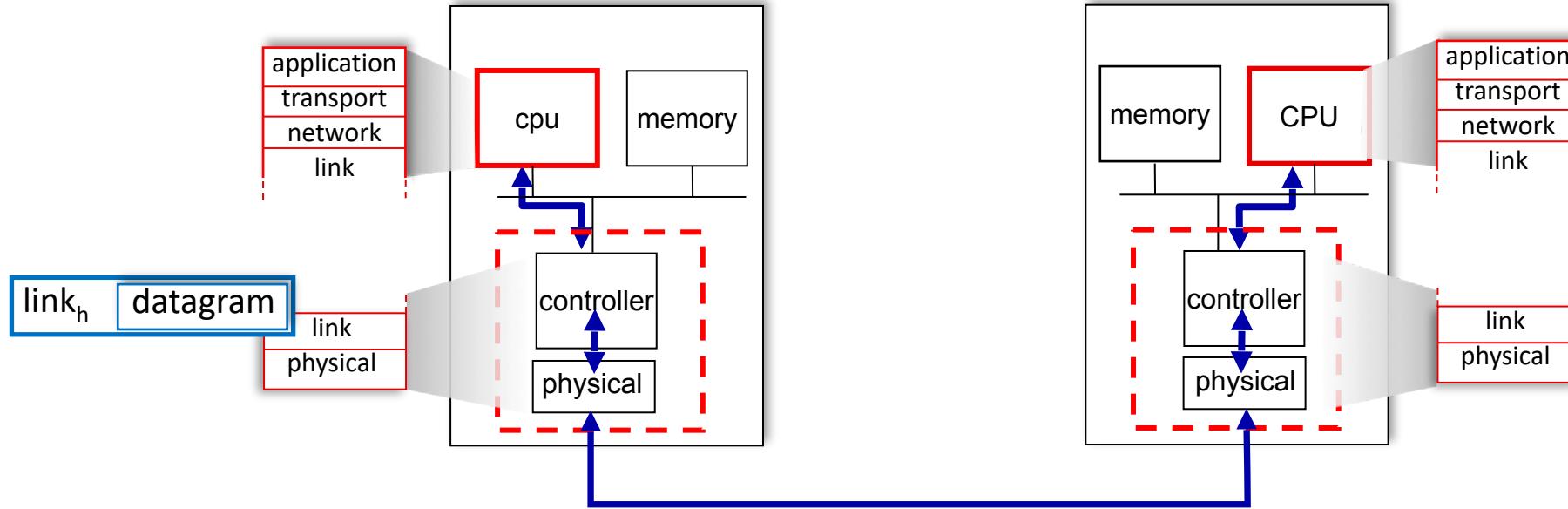
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Interfaces communicating



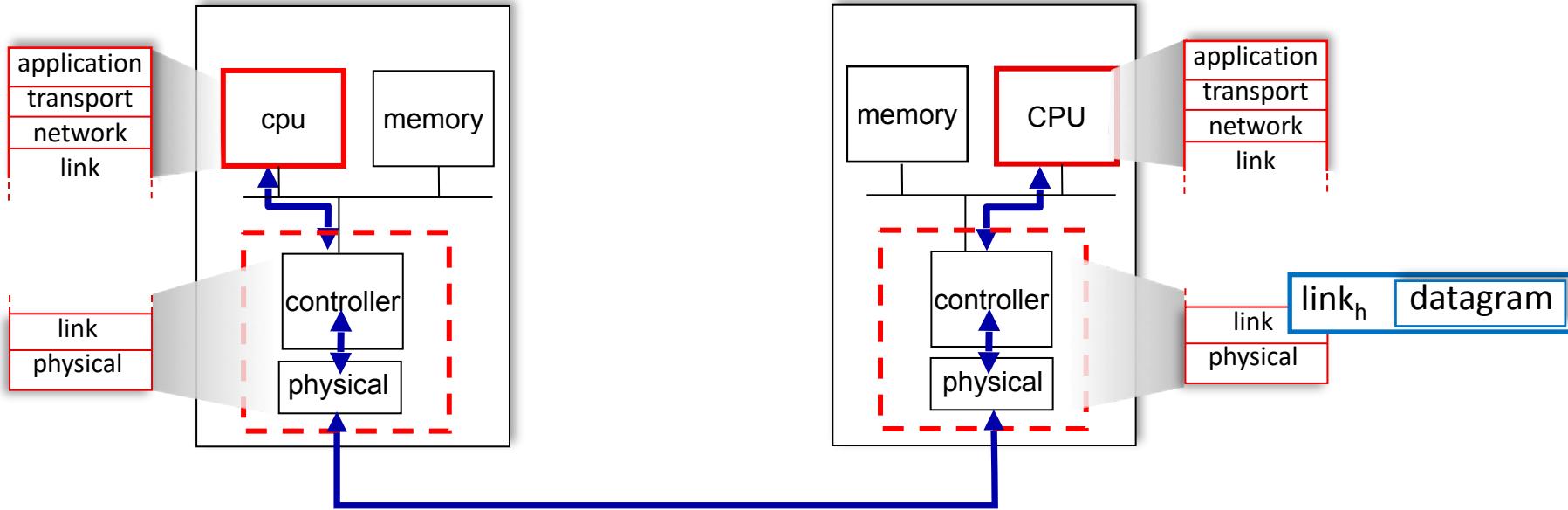
Interfaces communicating



sending side:

- encapsulates datagram in frame
- adds error checking bits, reliable data transfer, flow control, etc.

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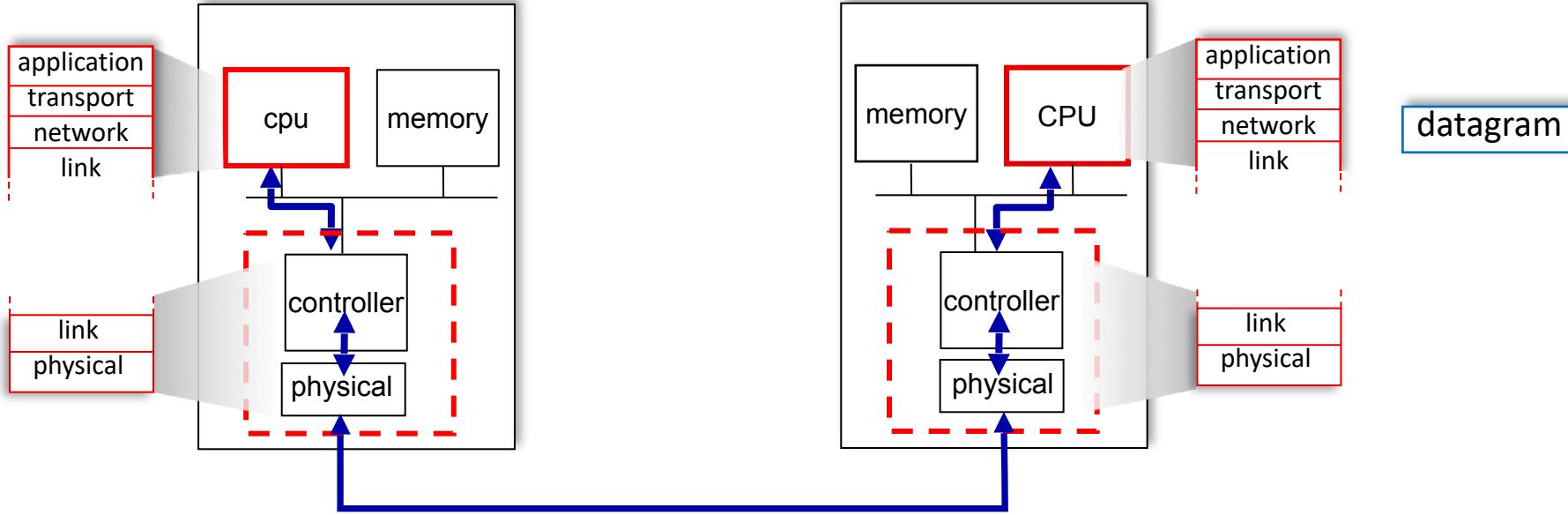
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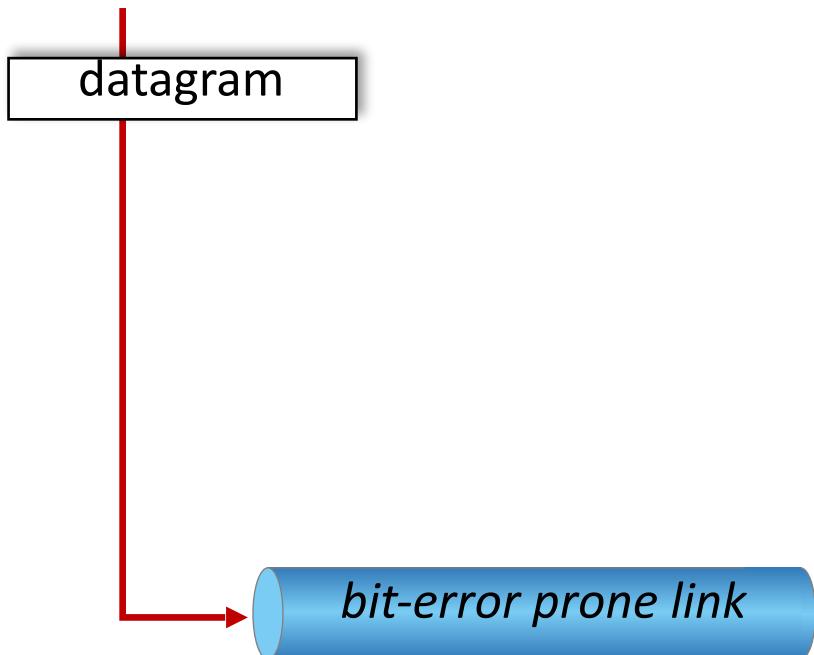
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Error detection

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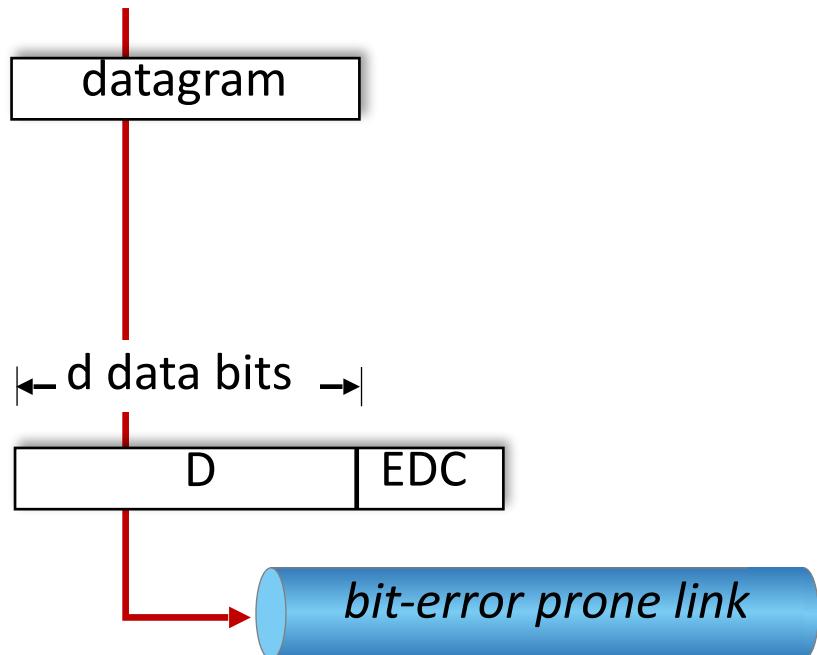
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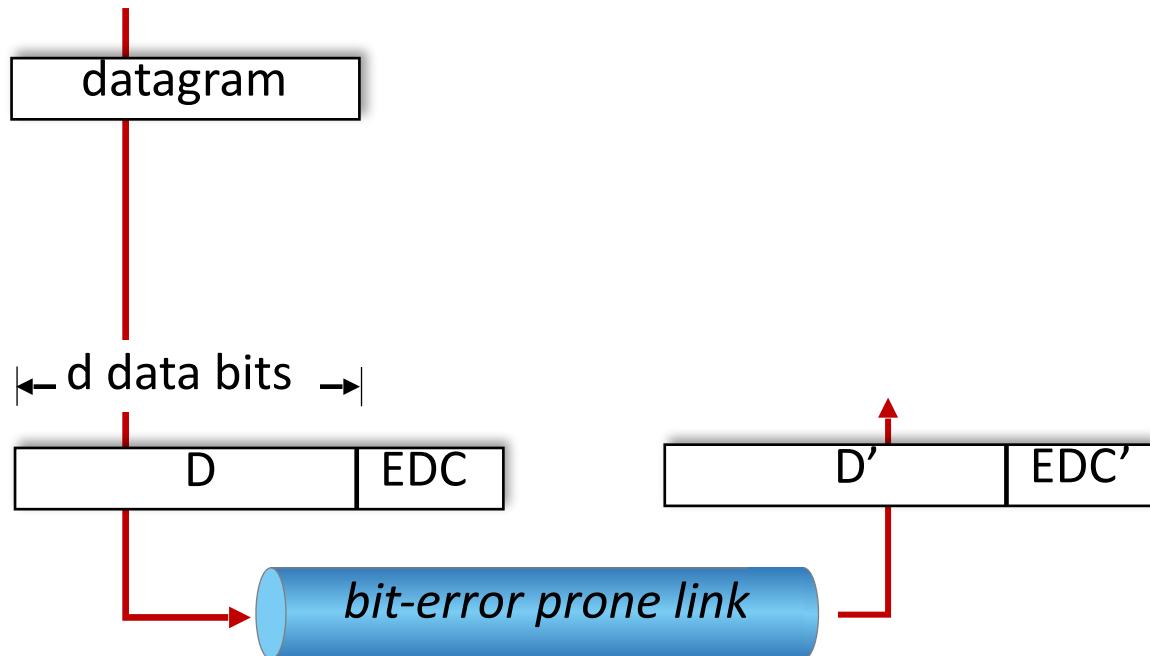
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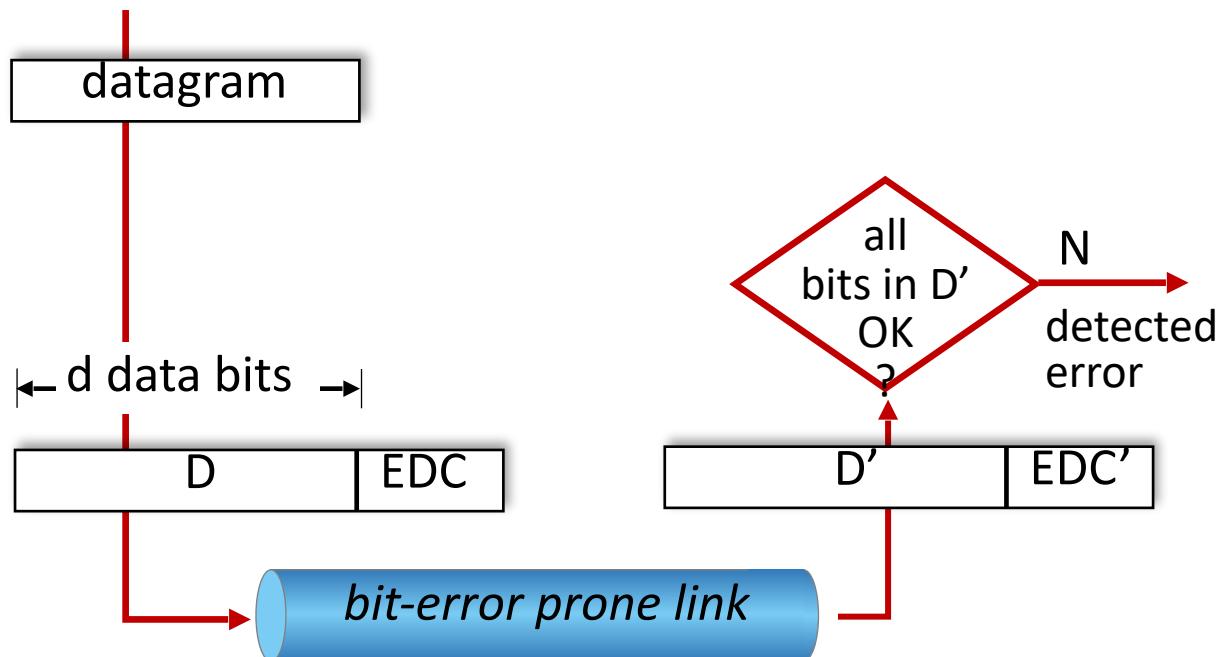
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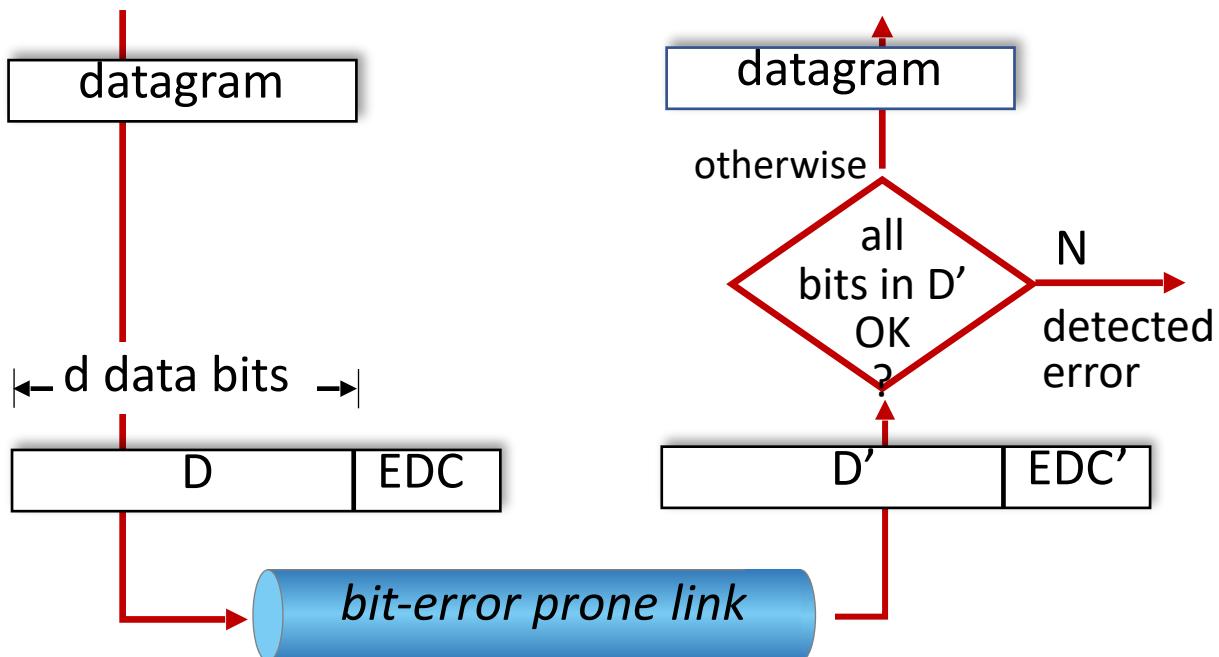
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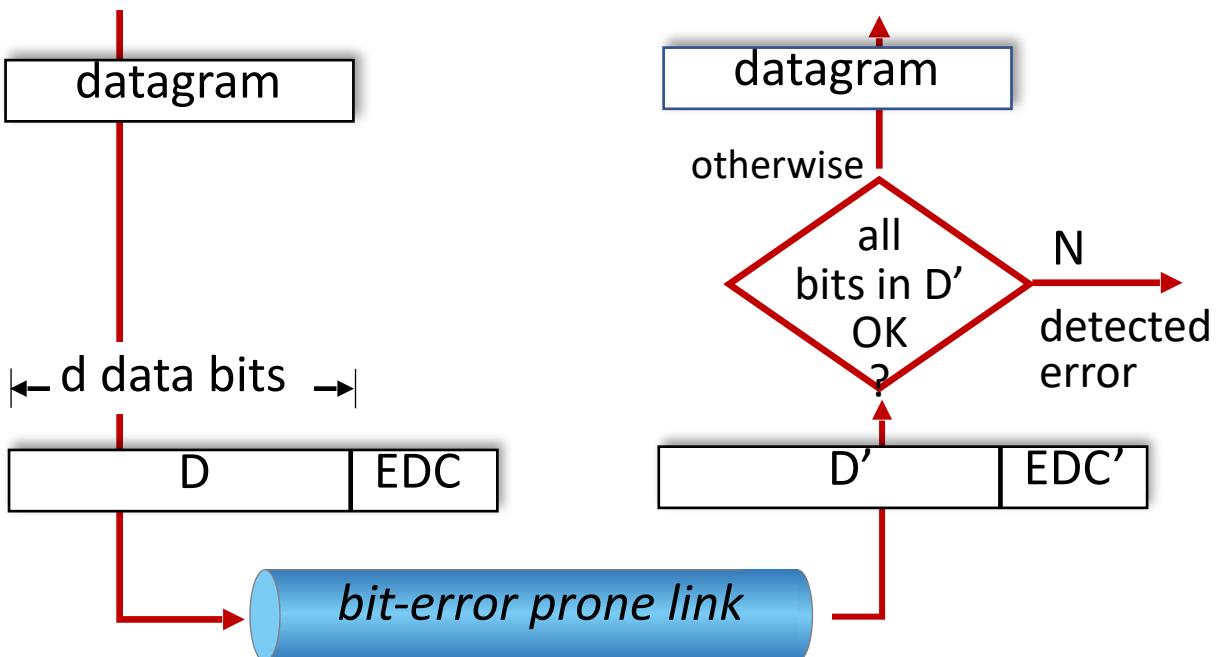
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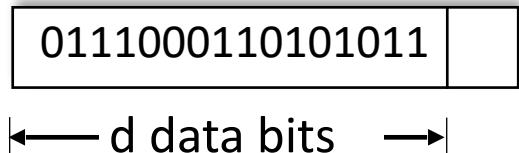
Error detection not 100% reliable!

- protocol may miss some errors, but rarely
- larger EDC field yields better detection and correction

Parity checking

single bit parity:

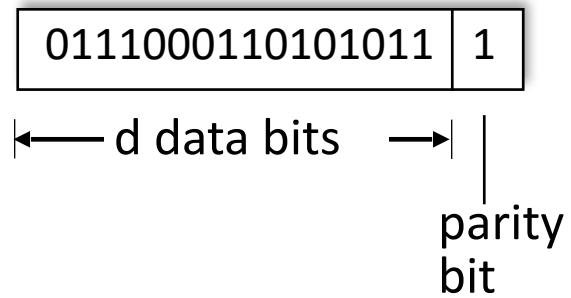
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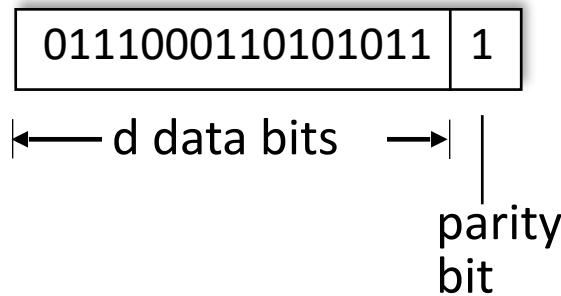


Even parity: set parity bit so there is an even number of 1's

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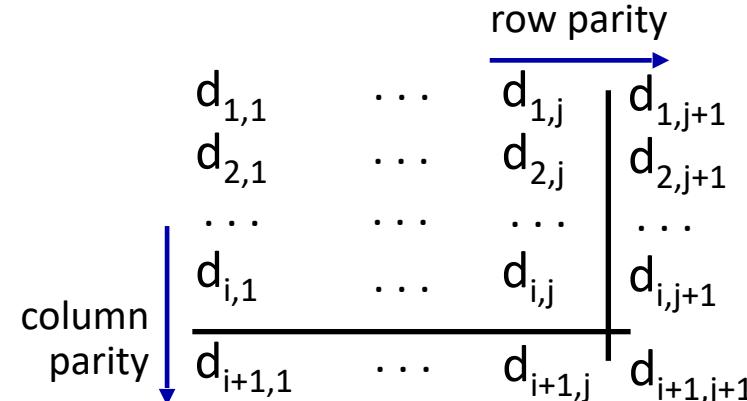
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two-dimensional bit parity:

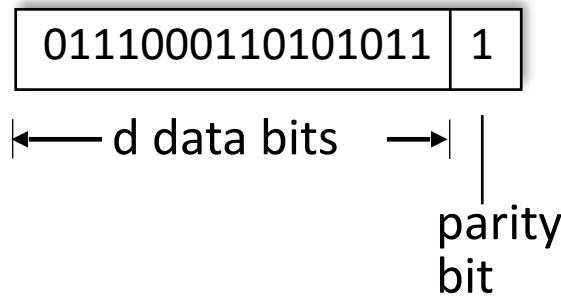
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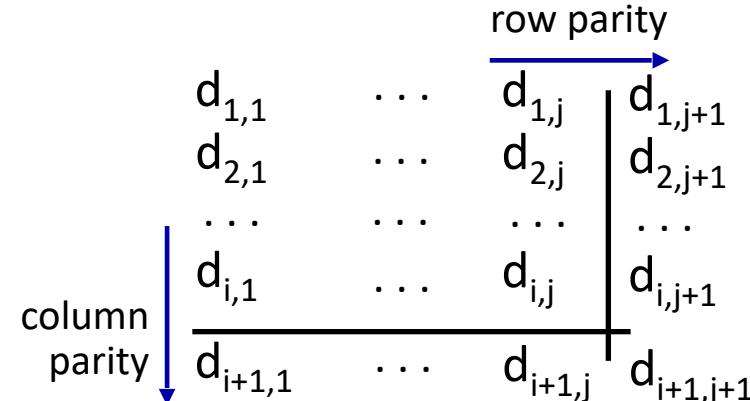
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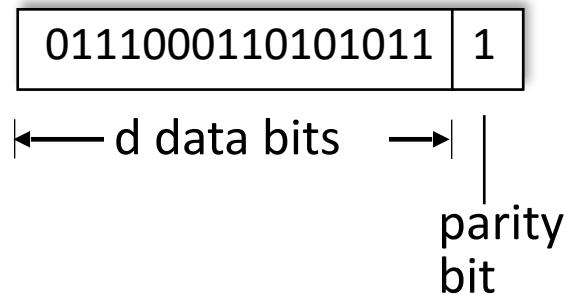


no errors: 1 0 1 0 1 | 1
1 1 1 1 0 | 0
0 1 1 1 0 | 1
—————
0 0 1 0 1 | 0

Parity checking

single bit parity:

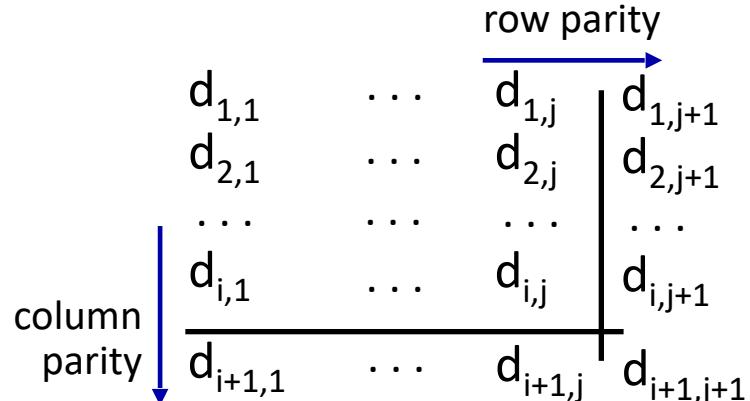
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no errors: 1 0 1 0 1 | 1
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detected
and
correctable
single-bit
error:

1 0 1 0 1 | 1
1 0 1 1 0 | 0 → parity error
0 1 1 1 0 | 1
—————
0 0 1 0 1 | 0
↓ parity error

Internet checksum (review)

Goal: detect errors (*i.e.*, flipped bits) in transmitted segment

sender:

- treat contents of UDP segment (including UDP header fields and IP addresses) as sequence of 16-bit integers
- **checksum:** addition (one's complement sum) of segment content
- checksum value put into UDP checksum field

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receiver:

- compute checksum of received segment
- check if computed checksum equals checksum field value:
 - not equal - error detected
 - equal - no error detected. *But maybe errors nonetheless? More later ...*

Cyclic Redundancy Check (CRC)

- more powerful error-detection coding
- **D**: data bits (given, think of these as a binary number)
- **G**: bit pattern (generator), of $r+1$ bits (given)

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goal: choose r CRC bits, **R**, such that $\langle D, R \rangle$ exactly divisible by **G** ($\text{mod } 2$)

- receiver knows **G**, divides $\langle D, R \rangle$ by **G**. If non-zero remainder: error detected!
- can detect all burst errors less than $r+1$ bits
- widely used in practice (Ethernet, 802.11 WiFi)

Cyclic Redundancy Check (CRC): example

We want:

$$D \cdot 2^r \text{ XOR } R = nG$$

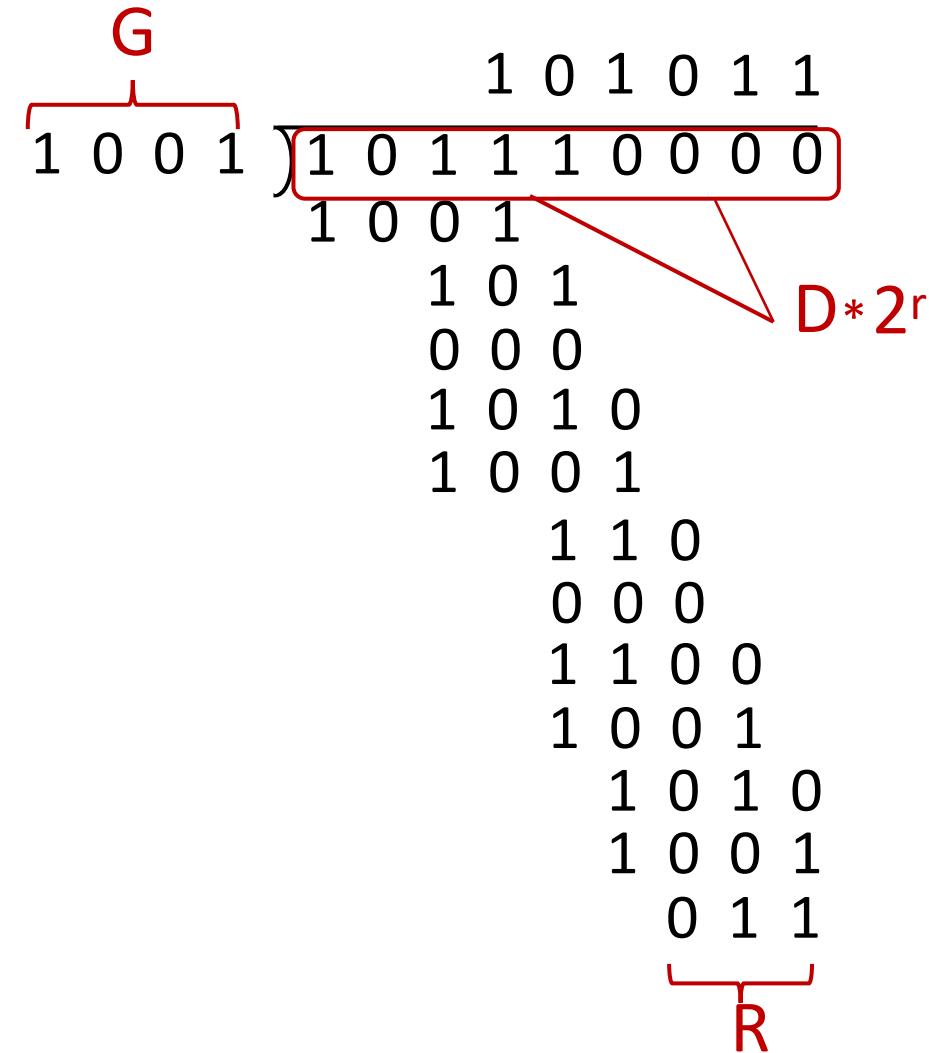
or equivalently:

$$D \cdot 2^r = nG \text{ XOR } R$$

or equivalently:

if we divide $D \cdot 2^r$ by G , want
remainder R to satisfy:

$$R = \text{remainder} \left[\frac{D \cdot 2^r}{G} \right]$$



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- **multiple access protocols**
- LANs
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Multiple access links, protocols

two types of “links”:

- point-to-point
 - point-to-point link between Ethernet switch, host
 - PPP for dial-up access
- broadcast (shared wire or medium)
 - old-fashioned Ethernet
 - upstream HFC in cable-based access network
 - 802.11 wireless LAN, 4G/5G, satellite



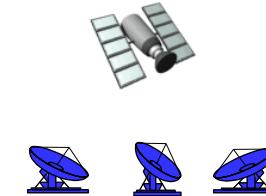
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shared radio: 4G/5G



shared radio: WiFi



shared radio: satellite

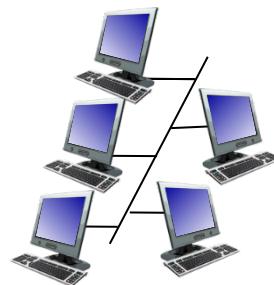


humans at a cocktail party
(shared air, acoustical)

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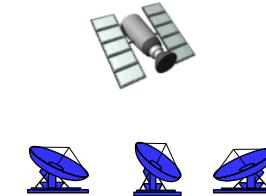
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Multiple access protocols

- single shared broadcast channel
- two or more simultaneous transmissions by nodes: interference
 - *collision* if node receives two or more signals at the same time

multiple access protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- communication about channel sharing must use channel itself!
 - no out-of-band channel for coordination

An ideal multiple access protocol

given: multiple access channel (MAC) of rate R bps

desiderata:

1. when one node wants to transmit, it can send at rate R .
2. when M nodes want to transmit, each can send at average rate R/M
3. fully decentralized:
 - no special node to coordinate transmissions
 - no synchronization of clocks, slots
4. simple

MAC protocols: taxonomy

three broad classes:

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- **channel partitioning**

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- allocate piece to node for exclusive use

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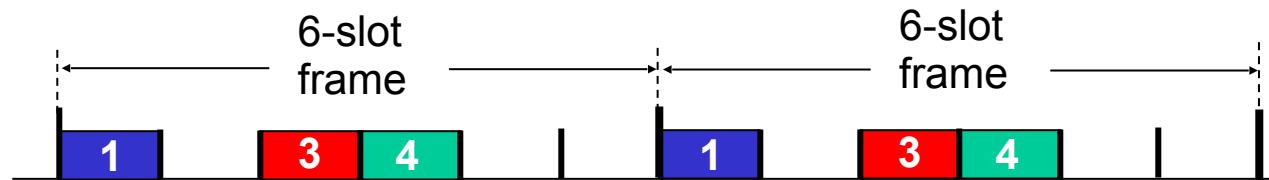
three broad classes:

- **channel partitioning**
 - divide channel into smaller “pieces” (time slots, frequency, code)
 - allocate piece to node for exclusive use
- *random access*
 - channel not divided, allow collisions
 - “recover” from collisions
- **“taking turns”**
 - nodes take turns, but nodes with more to send can take longer turns

Channel partitioning MAC protocols: TDMA

TDMA: time division multiple access

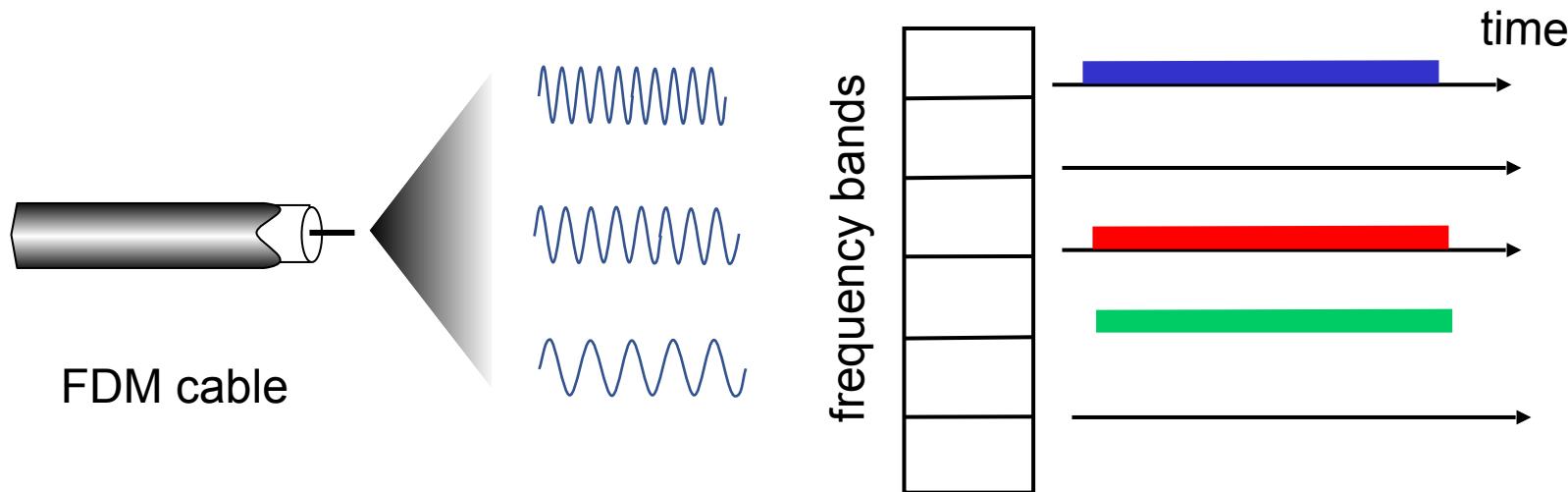
- access to channel in “rounds”
- each station gets fixed length slot (length = packet transmission time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle



Channel partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle
- example: 6-station LAN, 1,3,4 have packet to send, frequency bands 2,5,6 idle



Random access protocols

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- random access MAC protocol specifies:
 - how to detect collisions
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- examples of random access MAC protocols:
 - ALOHA, slotted ALOHA
 - CSMA, CSMA/CD, CSMA/CA

CSMA (carrier sense multiple access)

simple **CSMA**: listen before transmit:

- if channel sensed idle: transmit entire frame
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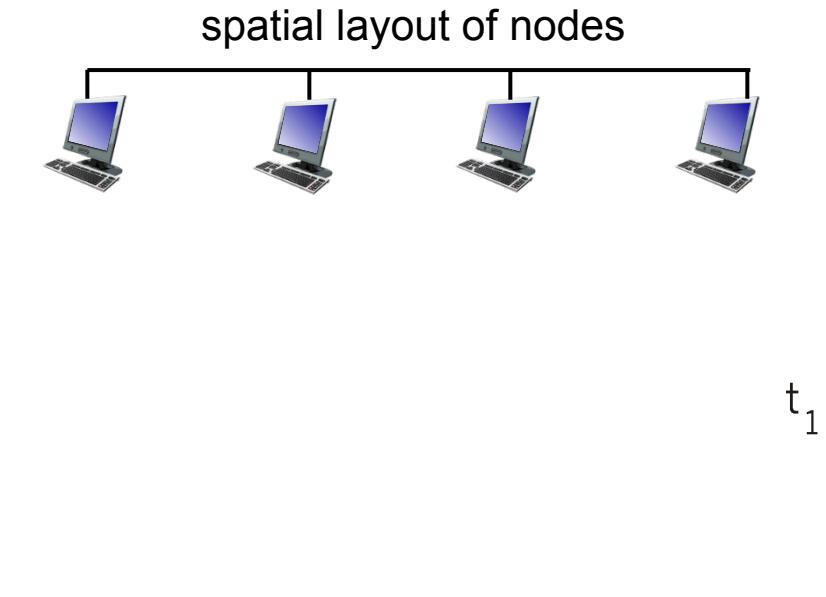
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CSMA/CD: CSMA with *collision detection*

- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage
- collision detection easy in wired, difficult with wireless
- human analogy: the polite conversationalist

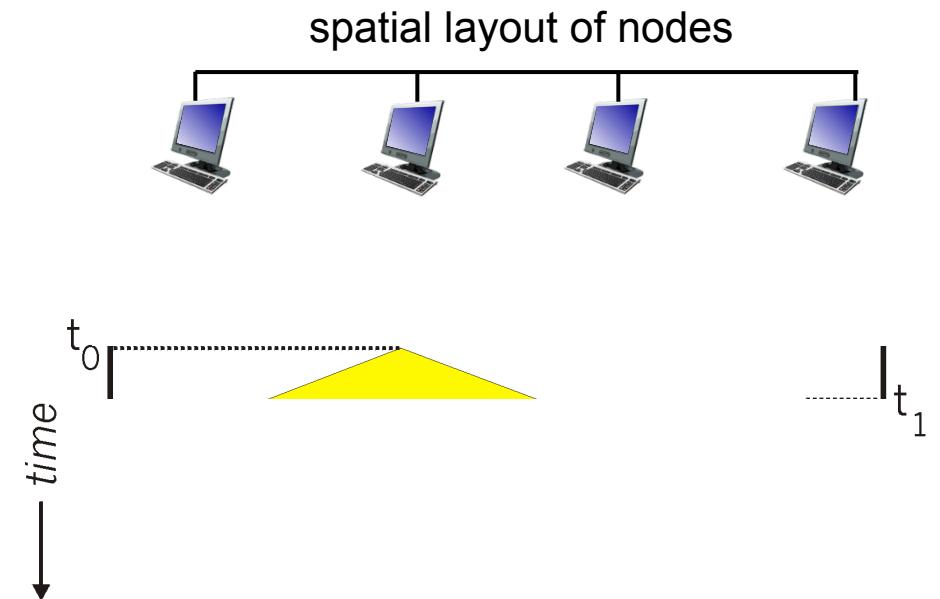
CSMA: collisions

- collisions *can* still occur with carrier sensing:
 - propagation delay means two nodes may not hear each other's just-started transmission
- **collision:** entire packet transmission time wasted
 - distance & propagation delay play role in determining collision probability



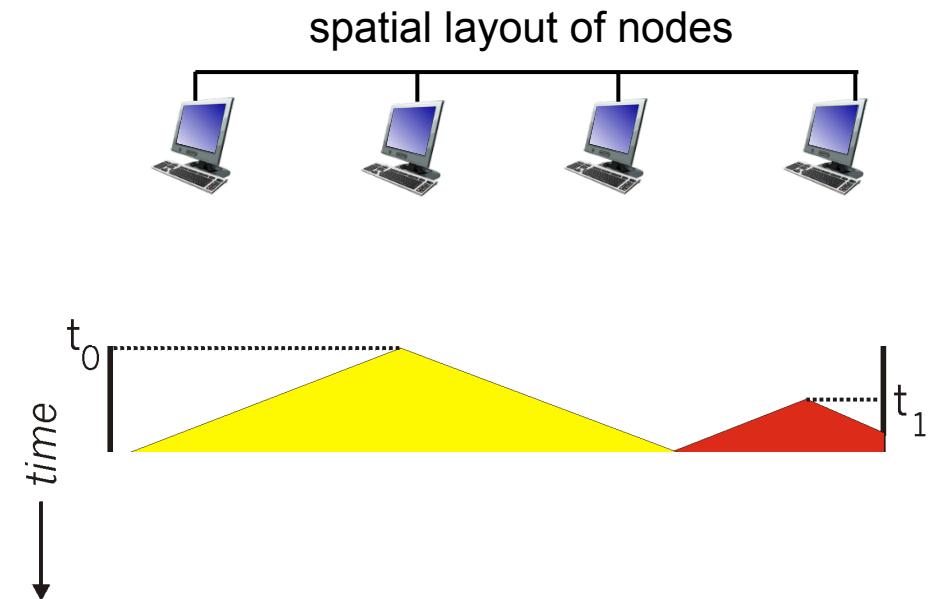
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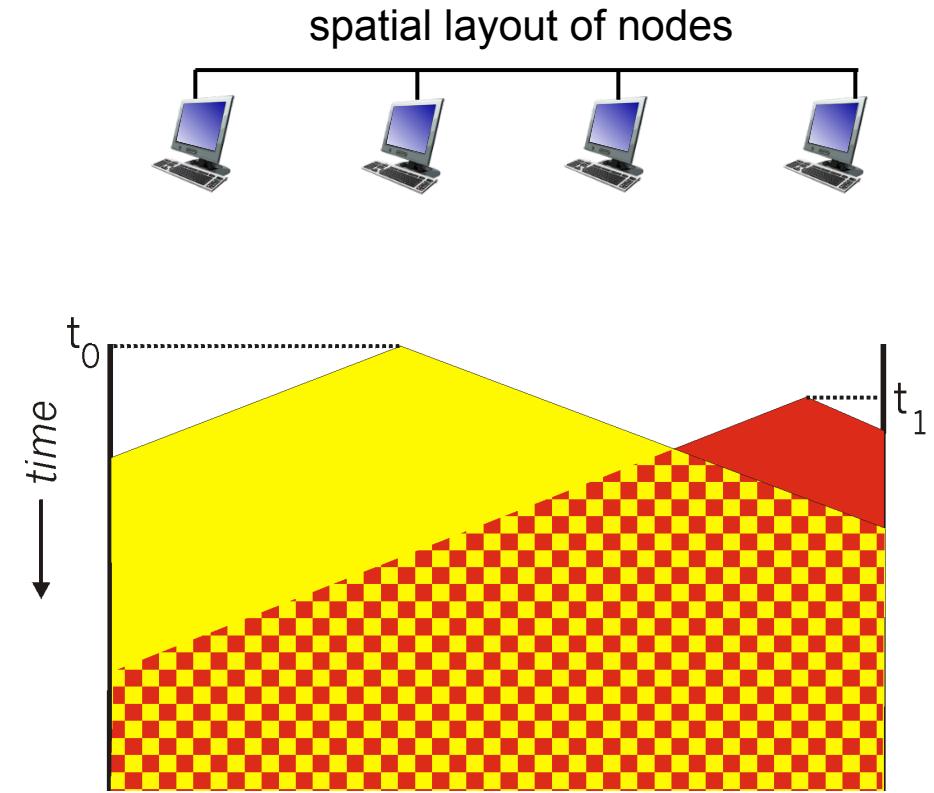
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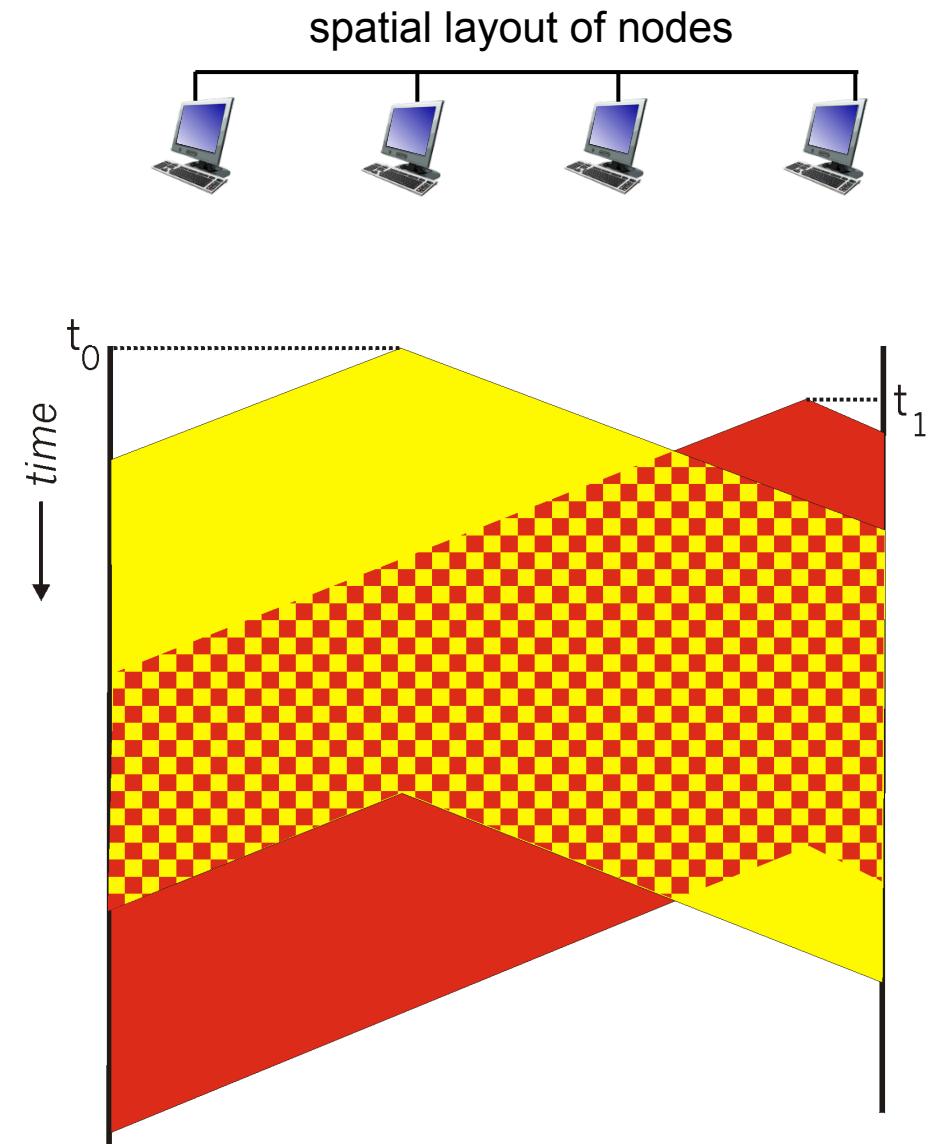
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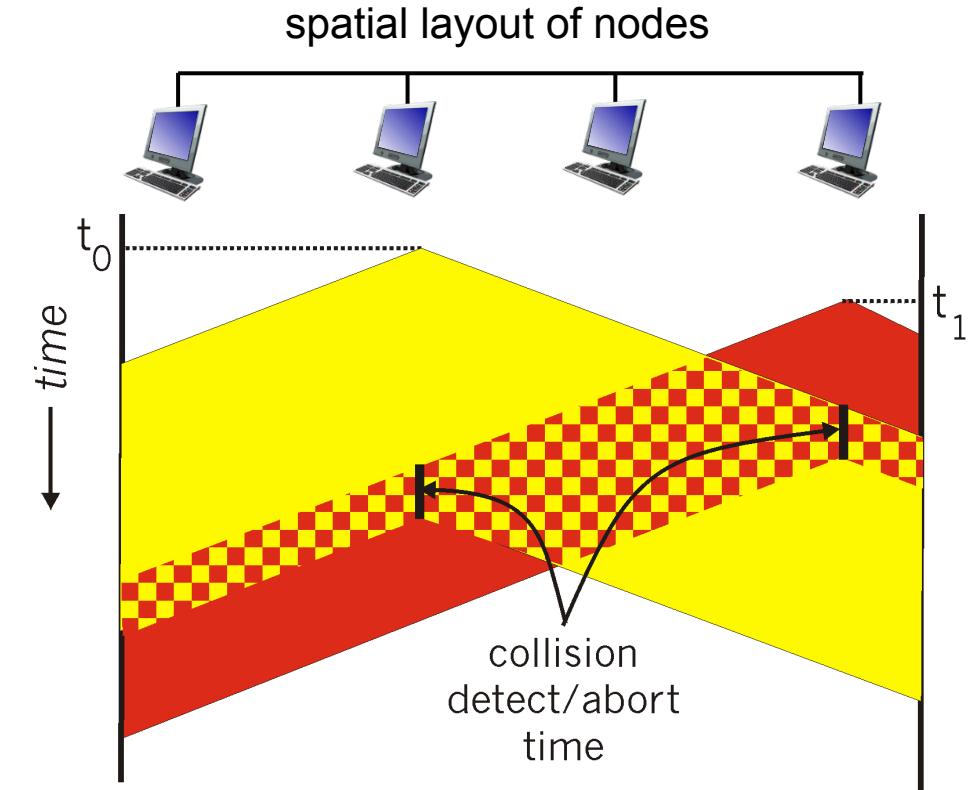
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CSMA/CD:

- CSMA/CS reduces the amount of time wasted in collisions
 - transmission aborted on collision detection



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Ethernet CSMA/CD algorithm

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 - after m th collision, NIC chooses K at random from $\{0,1,2, \dots, 2^m-1\}$. NIC waits $K \cdot 512$ bit times, returns to Step 2
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“Taking turns” MAC protocols

channel partitioning MAC protocols:

- share channel *efficiently* and *fairly* at high load
- inefficient at low load: delay in channel access, $1/N$ bandwidth allocated even if only 1 active node!

random access MAC protocols

- efficient at low load: single node can fully utilize channel
- high load: collision overhead

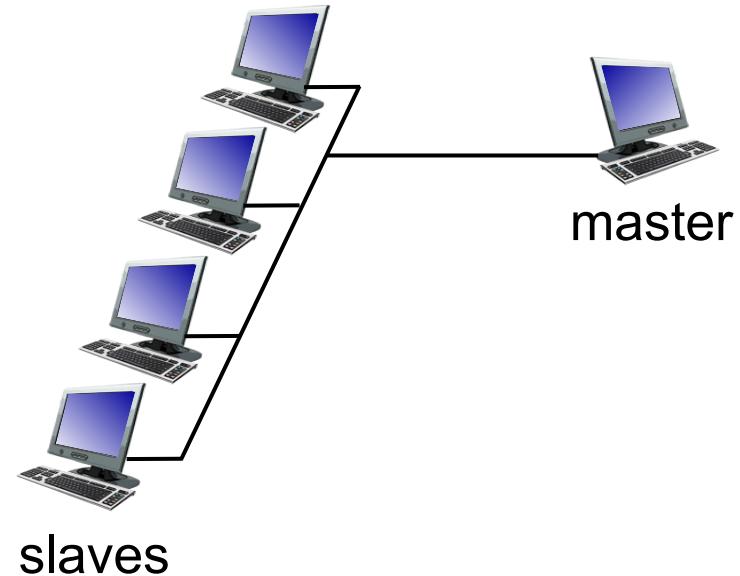
“taking turns” protocols

- look for best of both worlds!

“Taking turns” MAC protocols

polling:

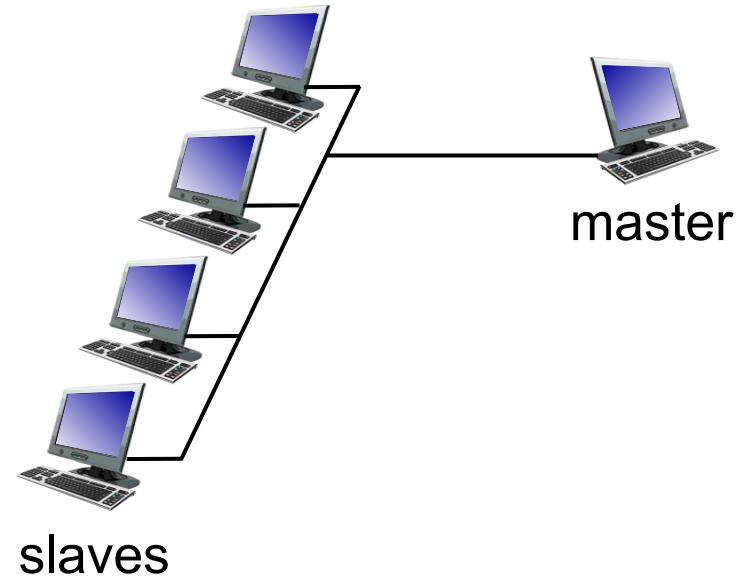
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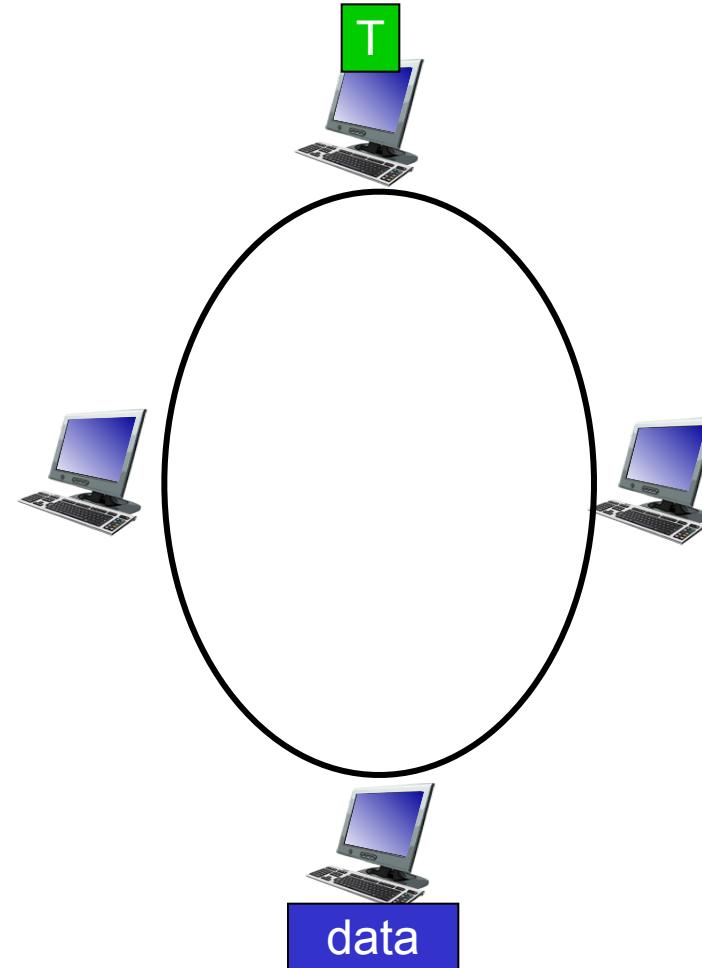
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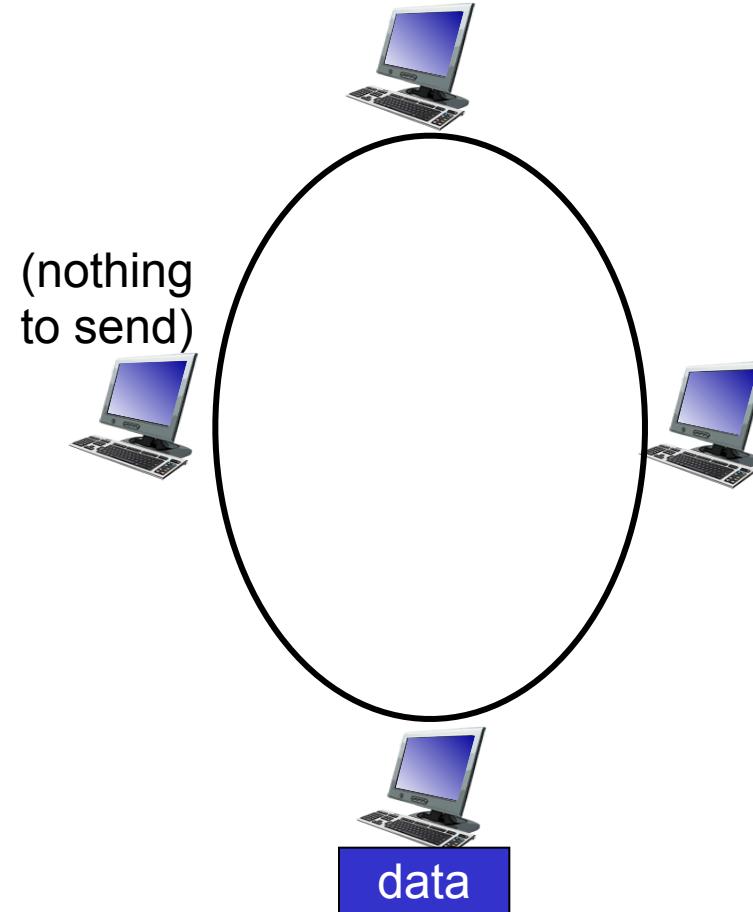
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- token message
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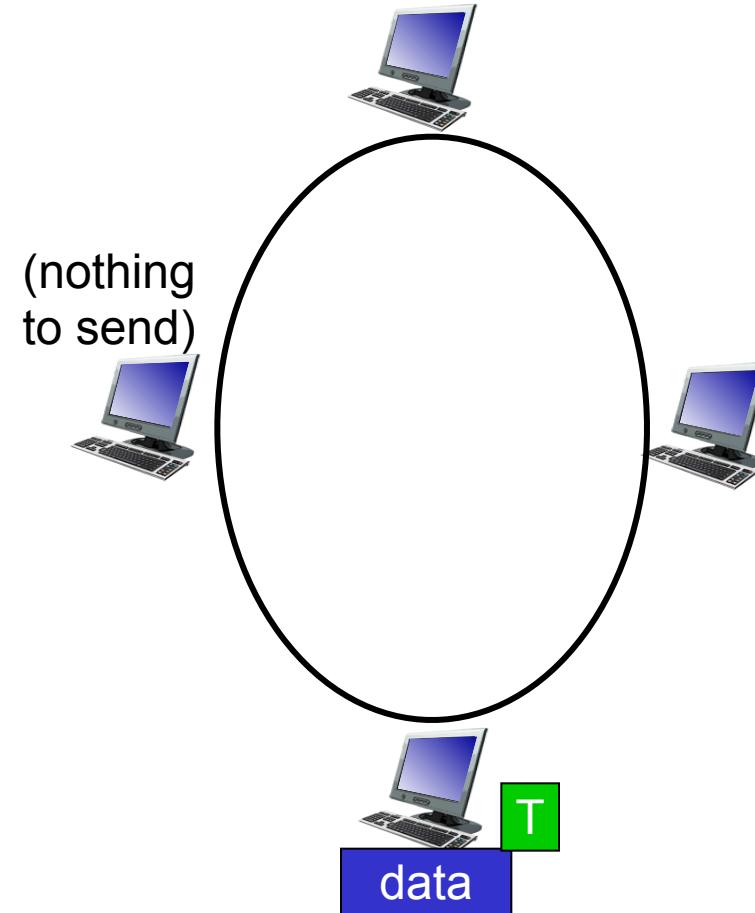
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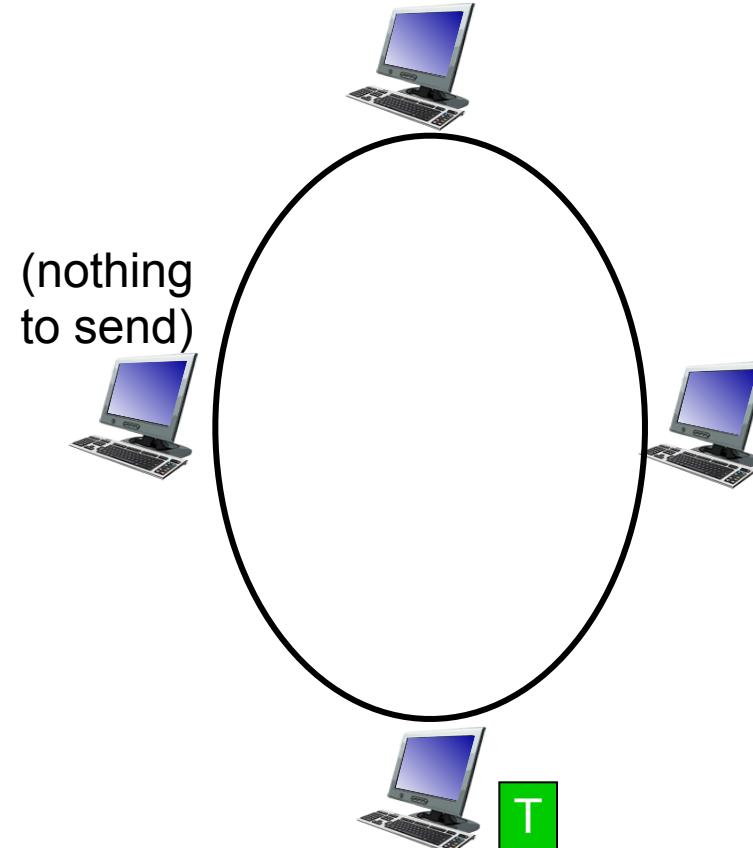
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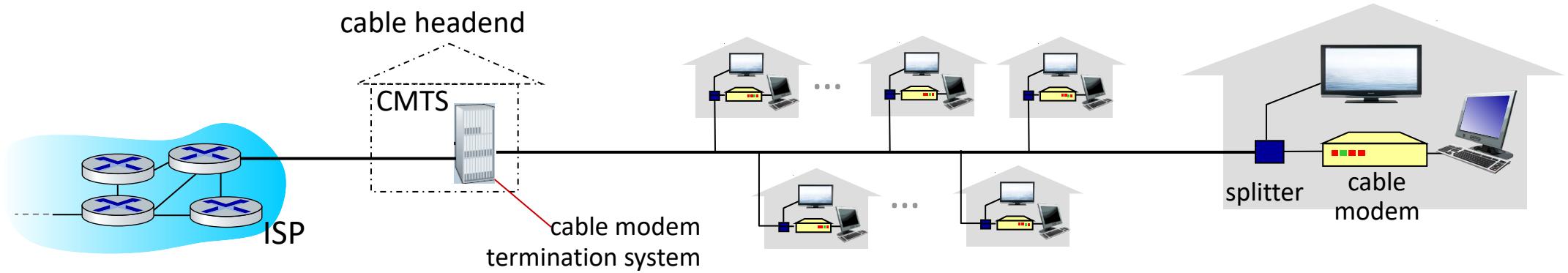
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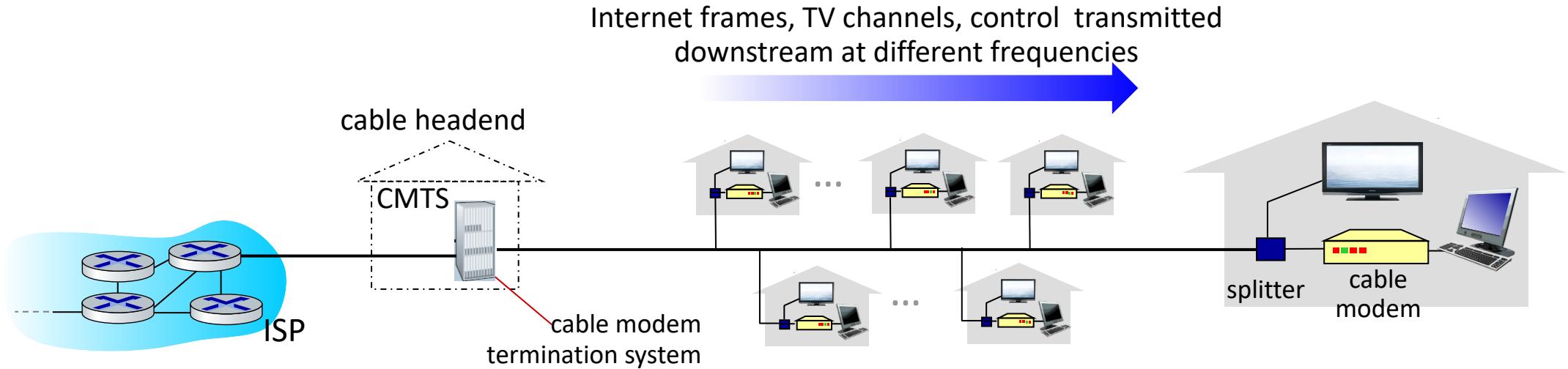
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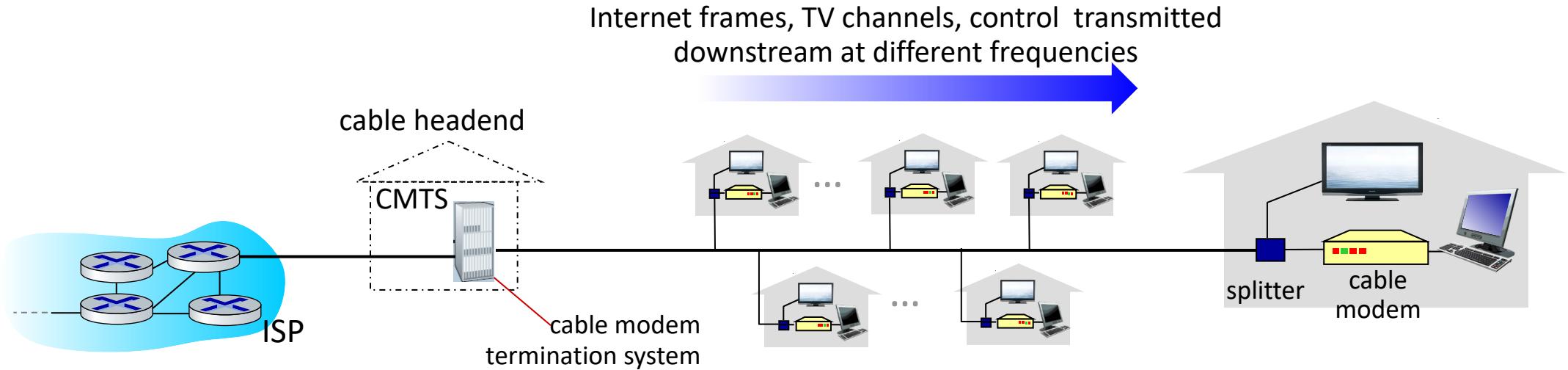
Cable access network: FDM, TDM and random access!



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Cable access network: FDM, TDM and random access!



- **multiple** downstream (broadcast) FDM channels: up to 1.6 Gbps/channel
 - single CMTS transmits into channels
- **multiple** upstream channels (up to 1 Gbps/channel)
 - **multiple access:** all users contend (random access) for certain upstream channel time slots; others assigned TDM

Summary of MAC protocols

- **channel partitioning**, by time, frequency or code
 - Time Division, Frequency Division
- **random access (dynamic)**,
 - ALOHA, S-ALOHA, CSMA, CSMA/CD
 - carrier sensing: easy in some technologies (wire), hard in others (wireless)
 - CSMA/CD used in Ethernet
 - CSMA/CA used in 802.11
- **taking turns**
 - polling from central site, token passing
 - Bluetooth, FDDI, token ring

Chapter 5: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
- datacenter networking
- a day in the life of a web request

MAC addresses

- 32-bit IP address:
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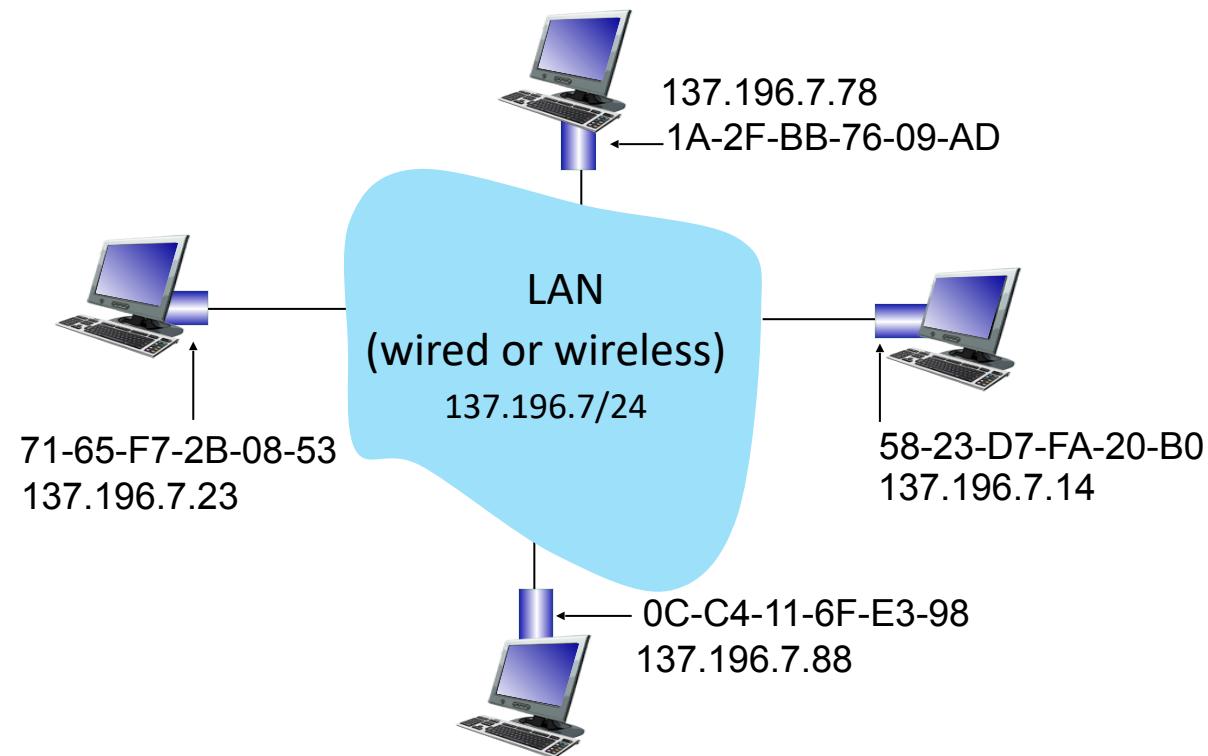
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 - e.g.: 1A-2F-BB-76-09-AD

*hexadecimal (base 16) notation
(each “numeral” represents 4 bits)*

MAC addresses

each interface on LAN

- has unique 48-bit **MAC** address
- has a locally unique 32-bit IP address (as we've seen)



MAC addresses

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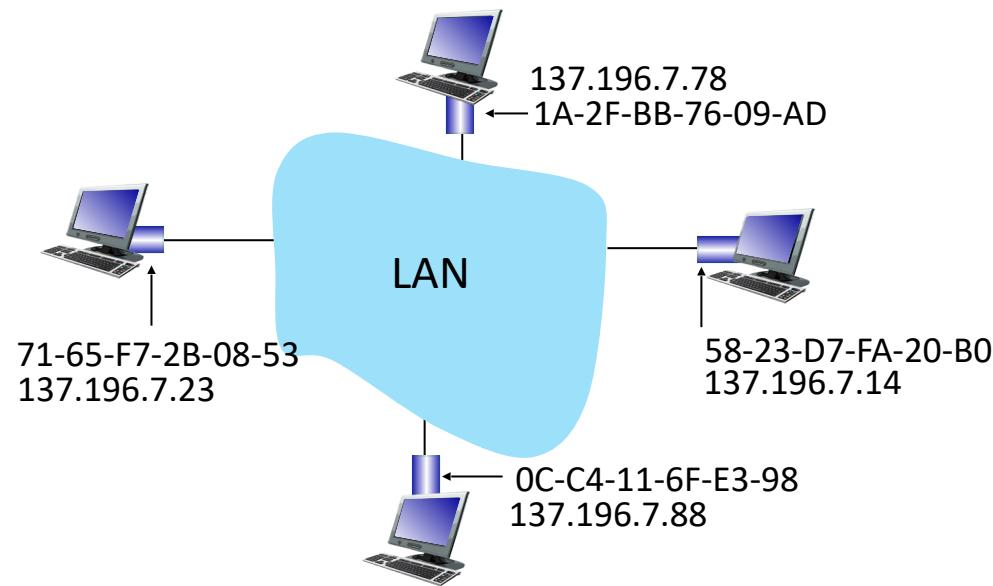
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ARP: address resolution protocol

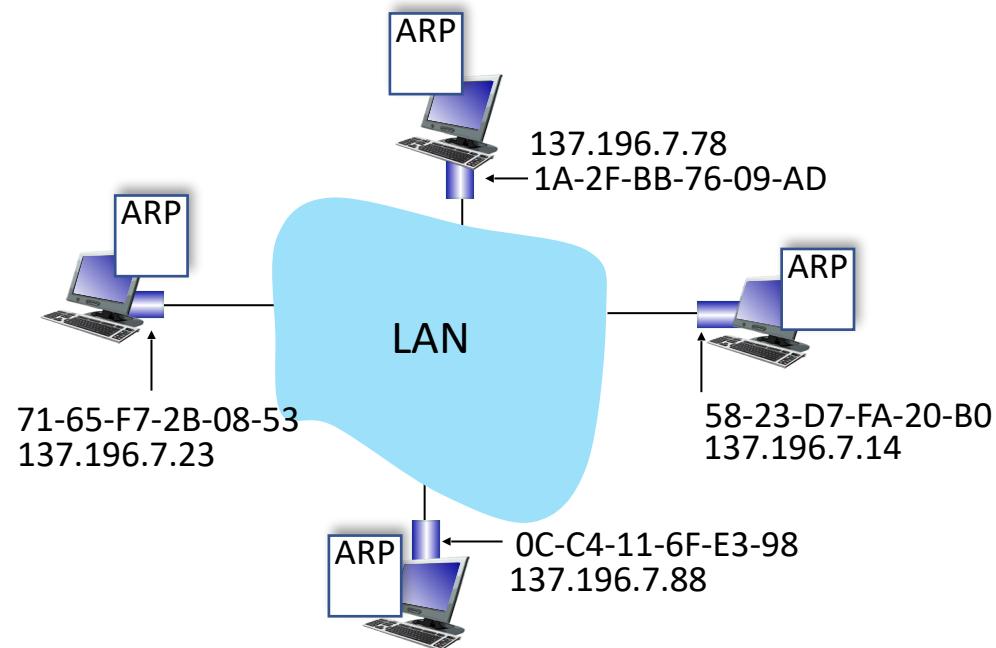
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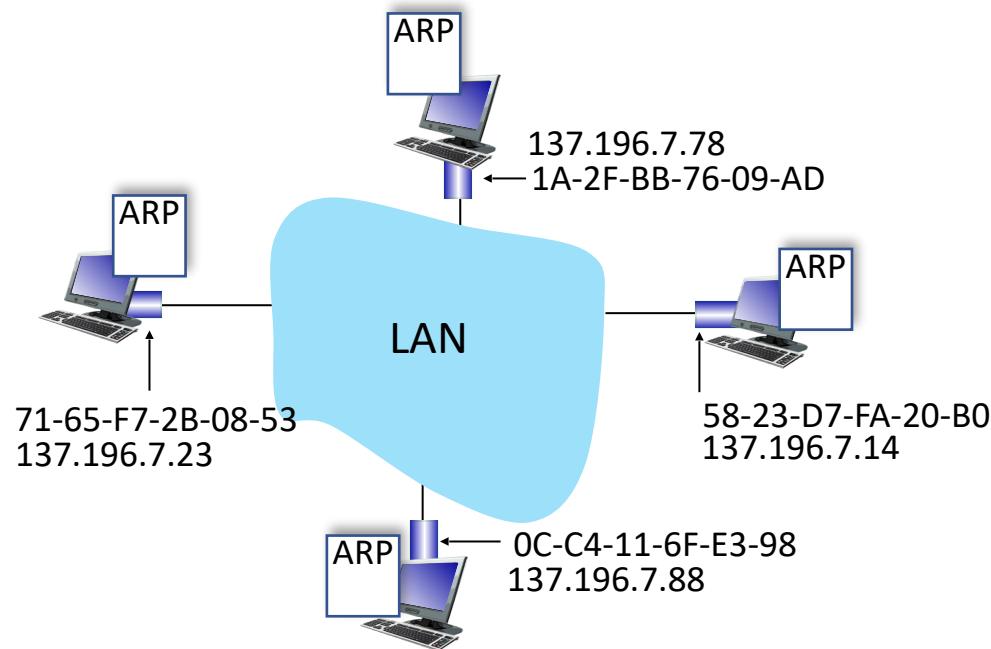
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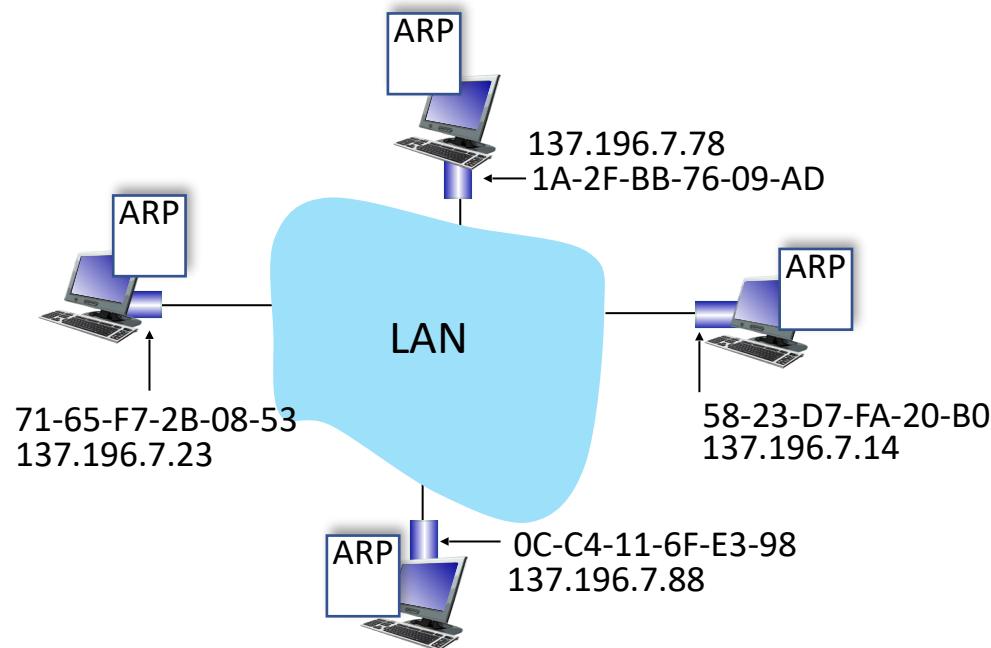


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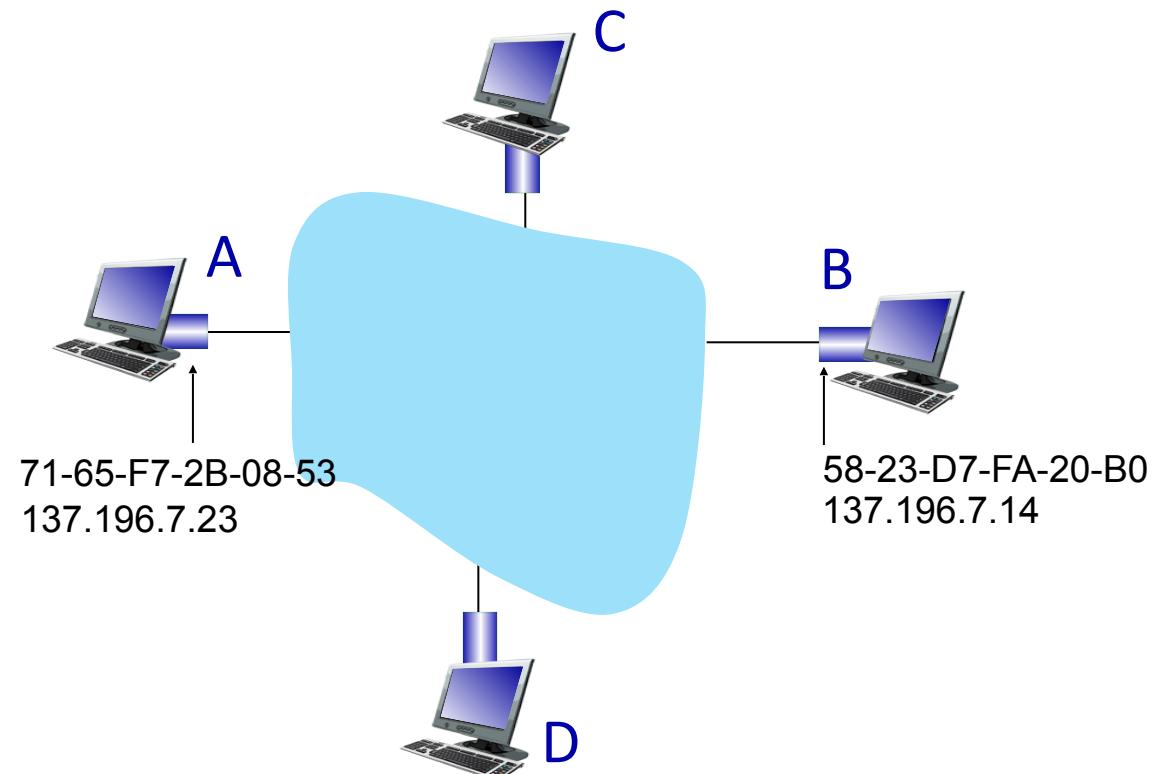
ARP table: each IP node (host, router) on LAN has table

- IP/MAC address mappings for some LAN nodes:
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- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

ARP protocol in action

example: A wants to send datagram to B

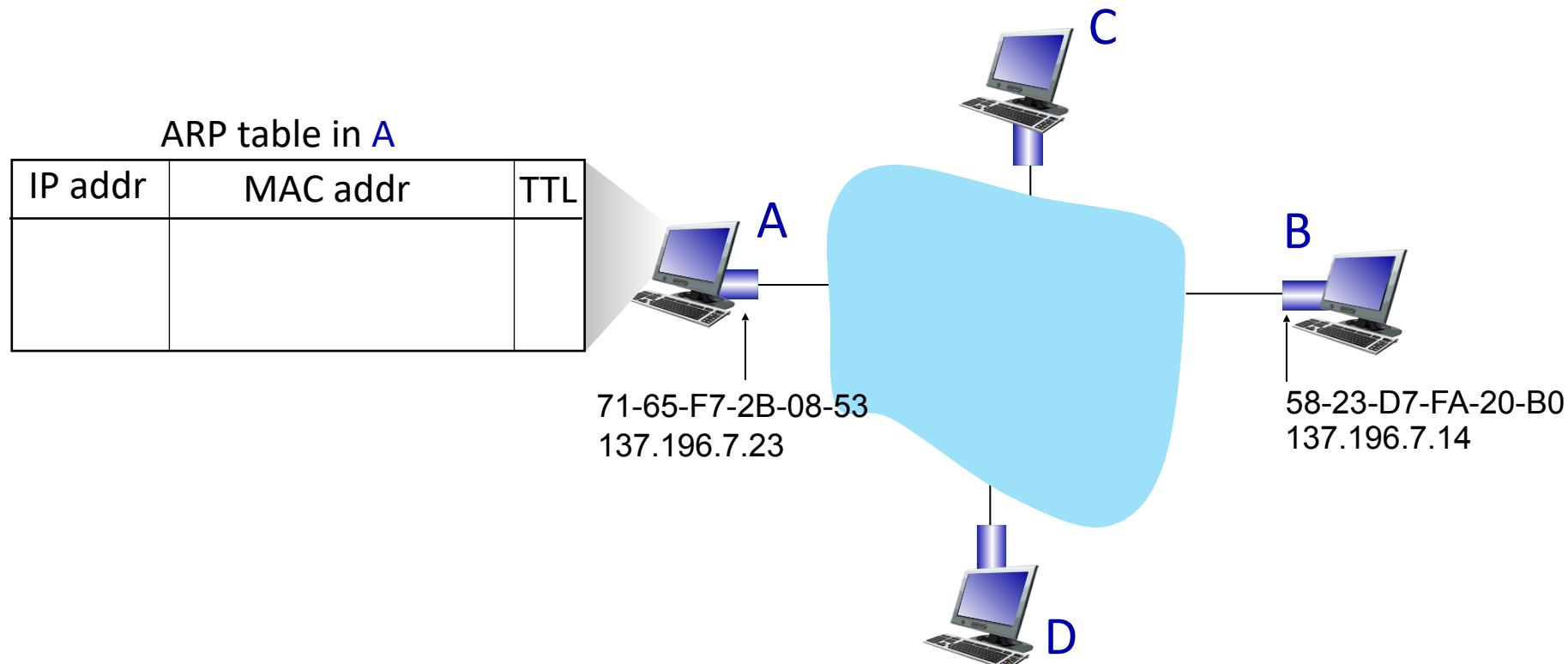
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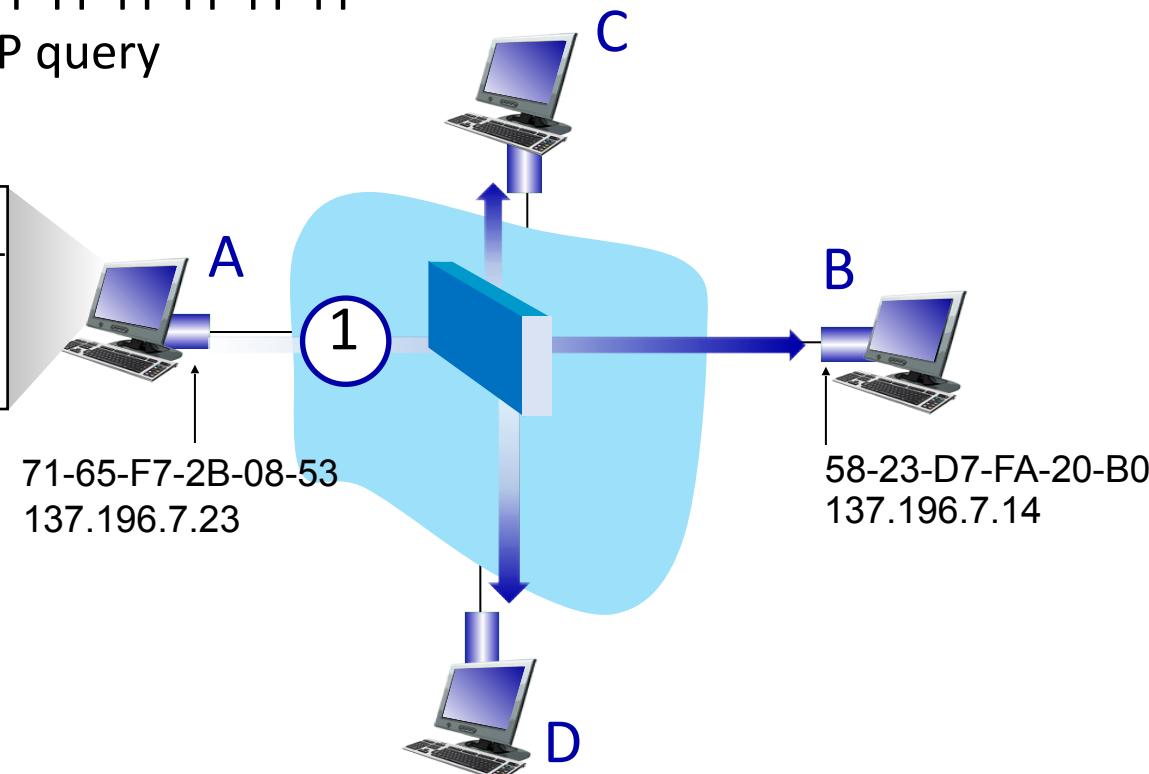
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A broadcasts ARP query, containing B's IP addr

- 1
- destination MAC address = FF-FF-FF-FF-FF-FF
 - all nodes on LAN receive ARP query

ARP table in A		
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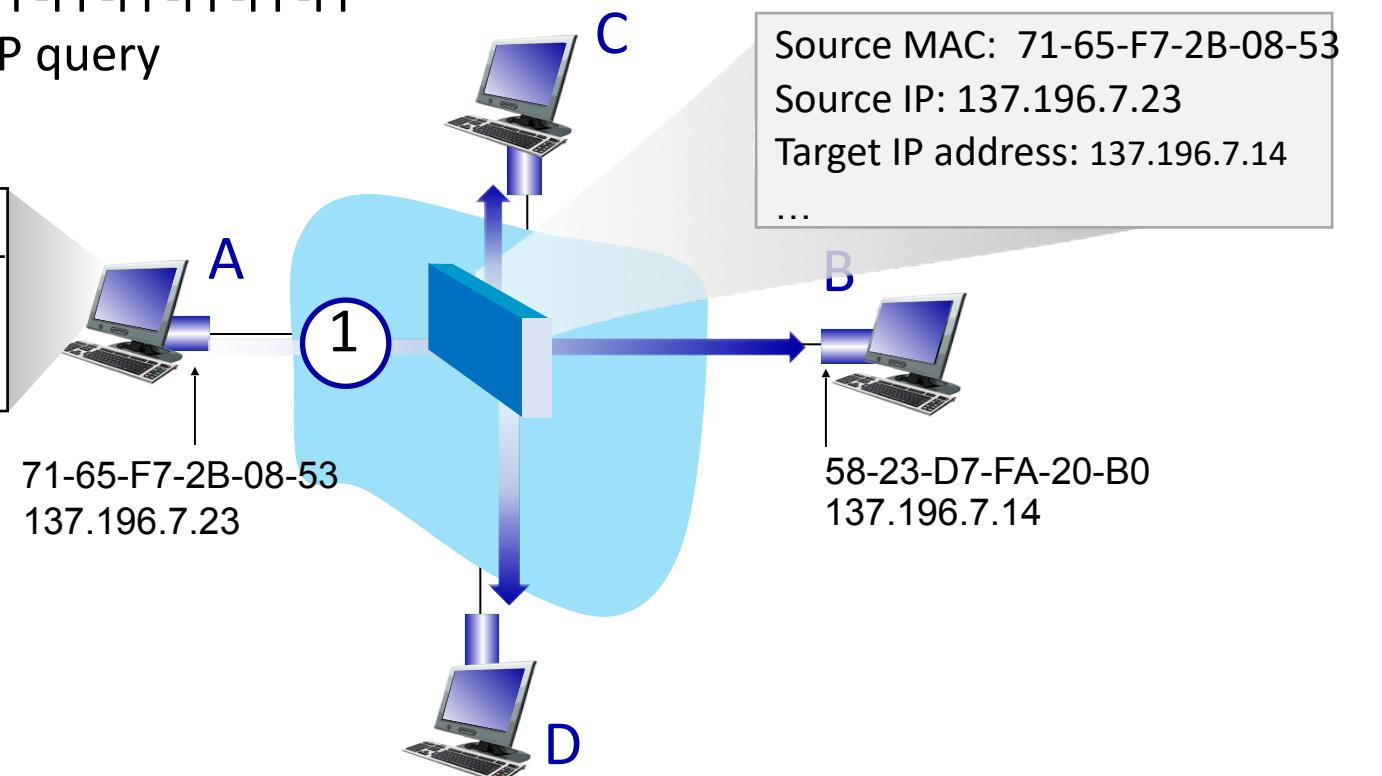
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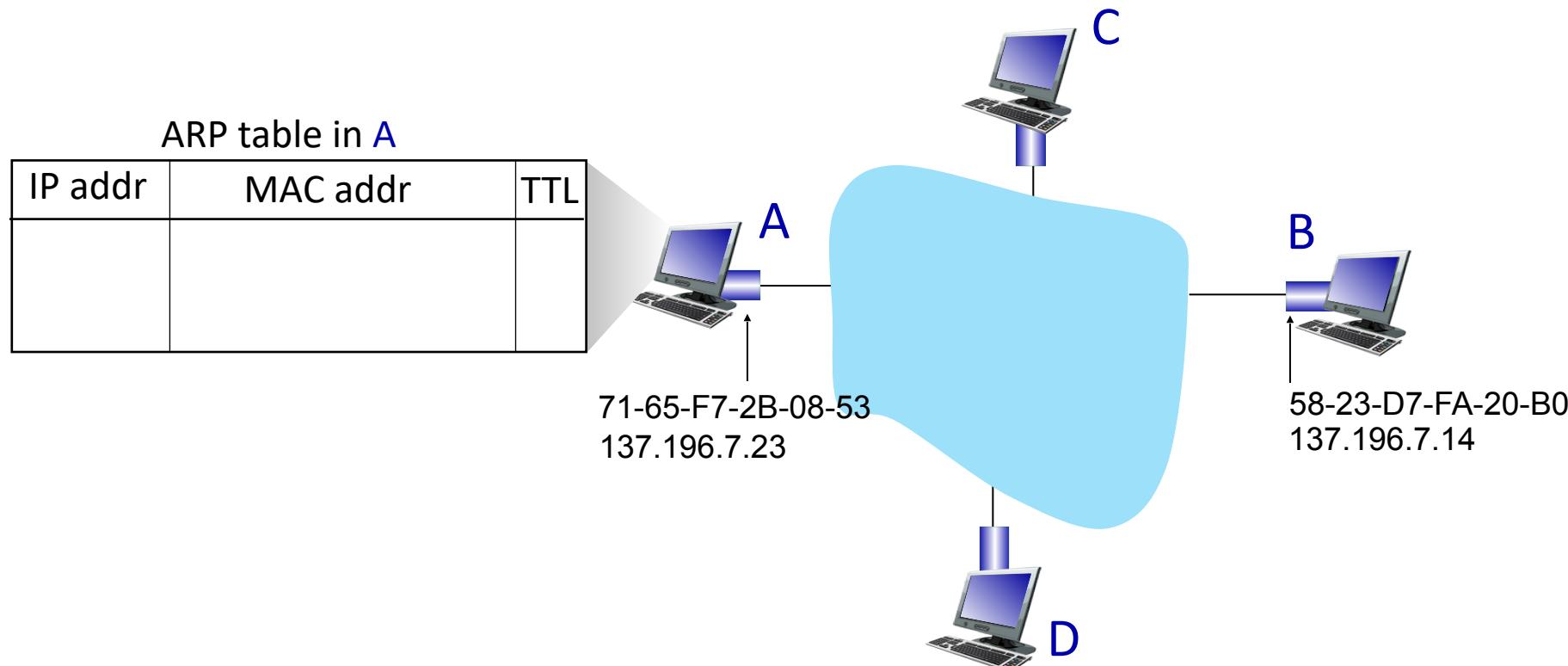
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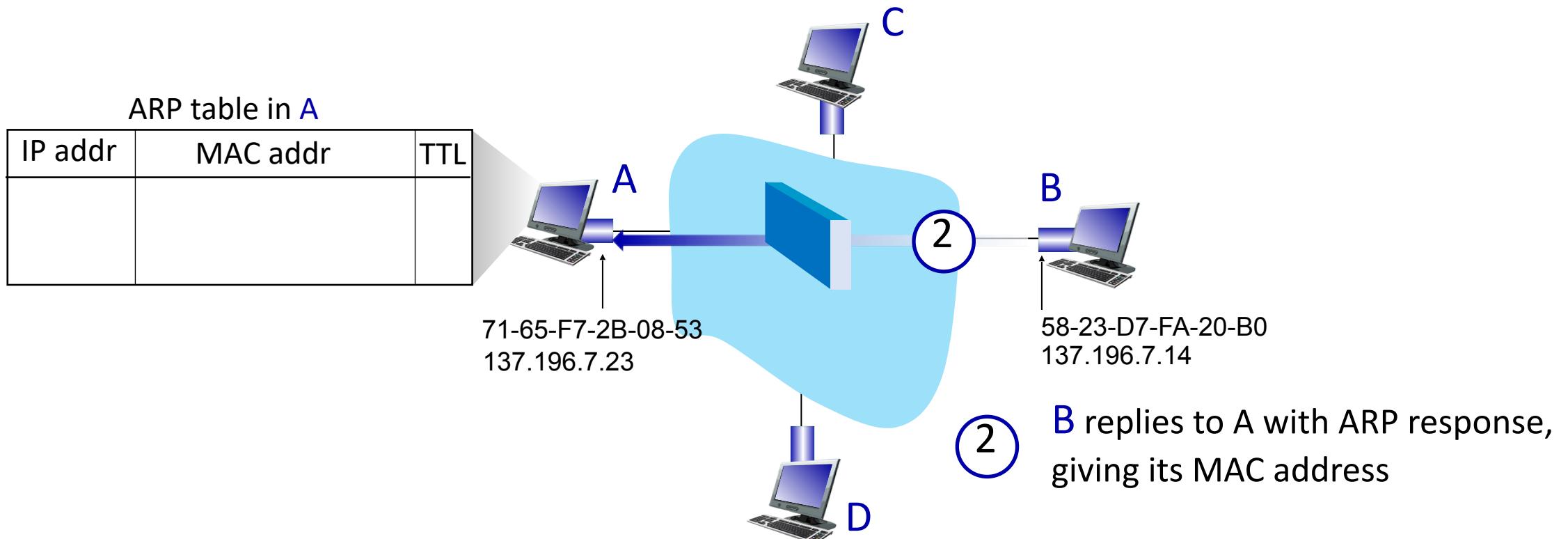
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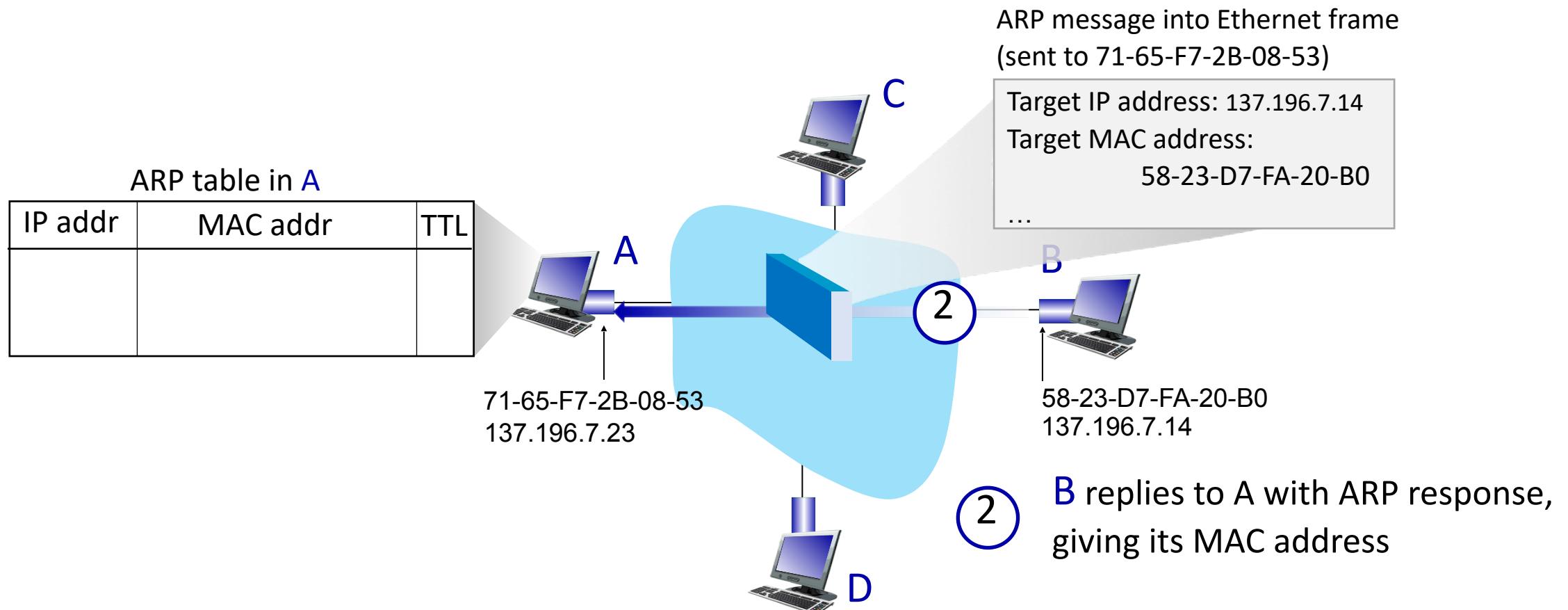
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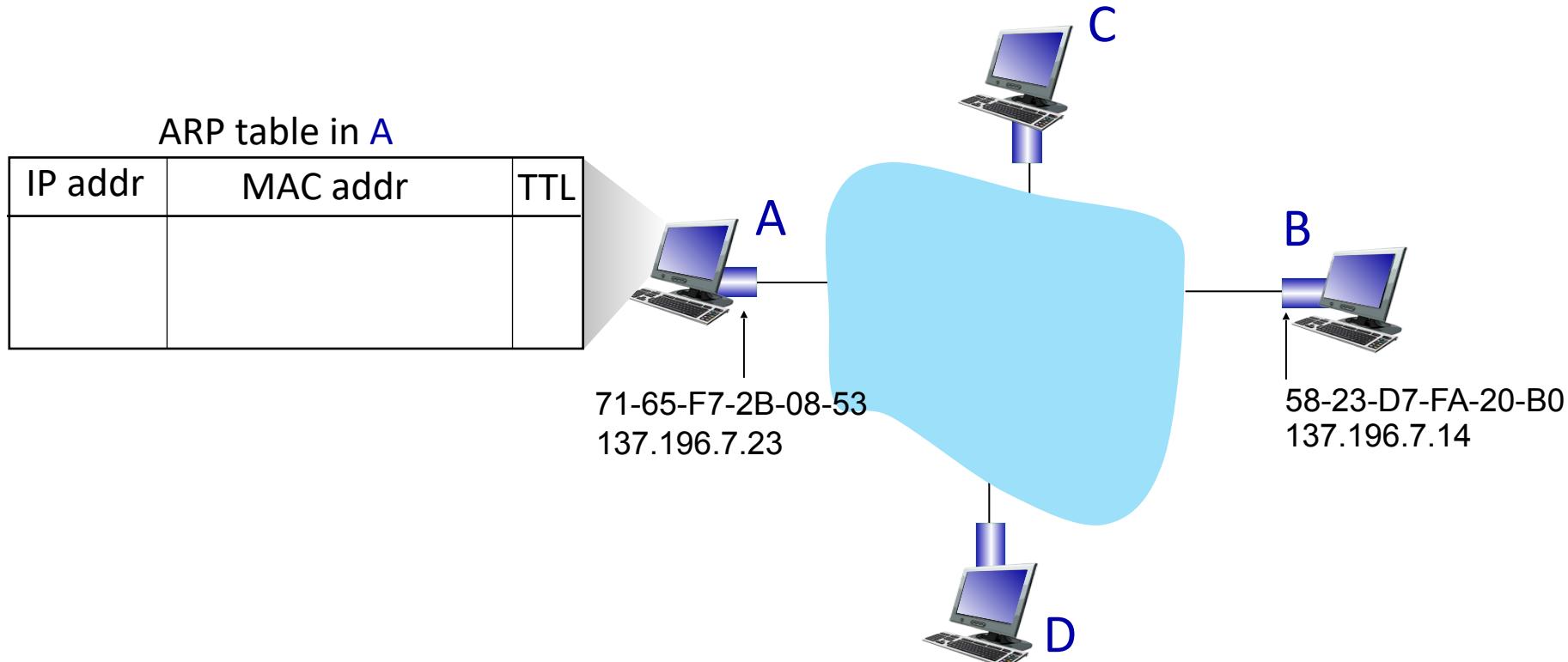
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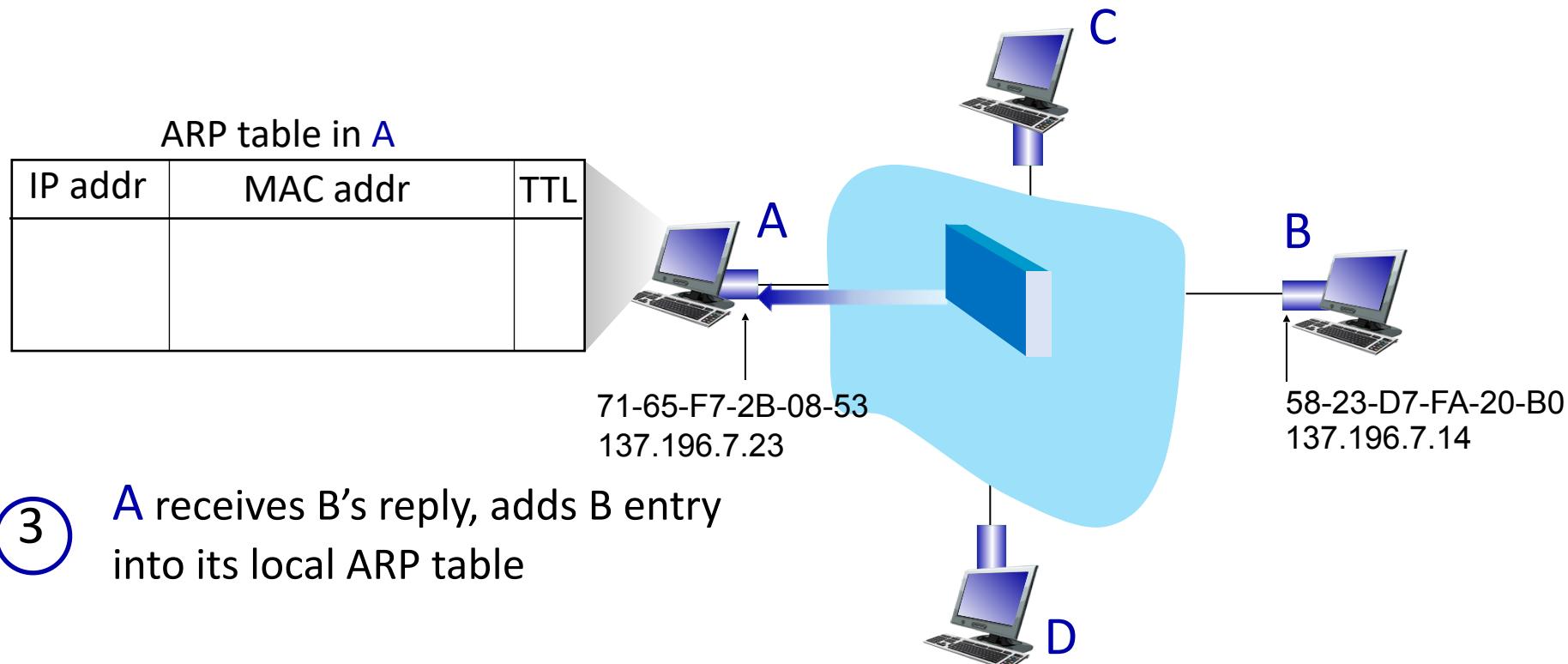
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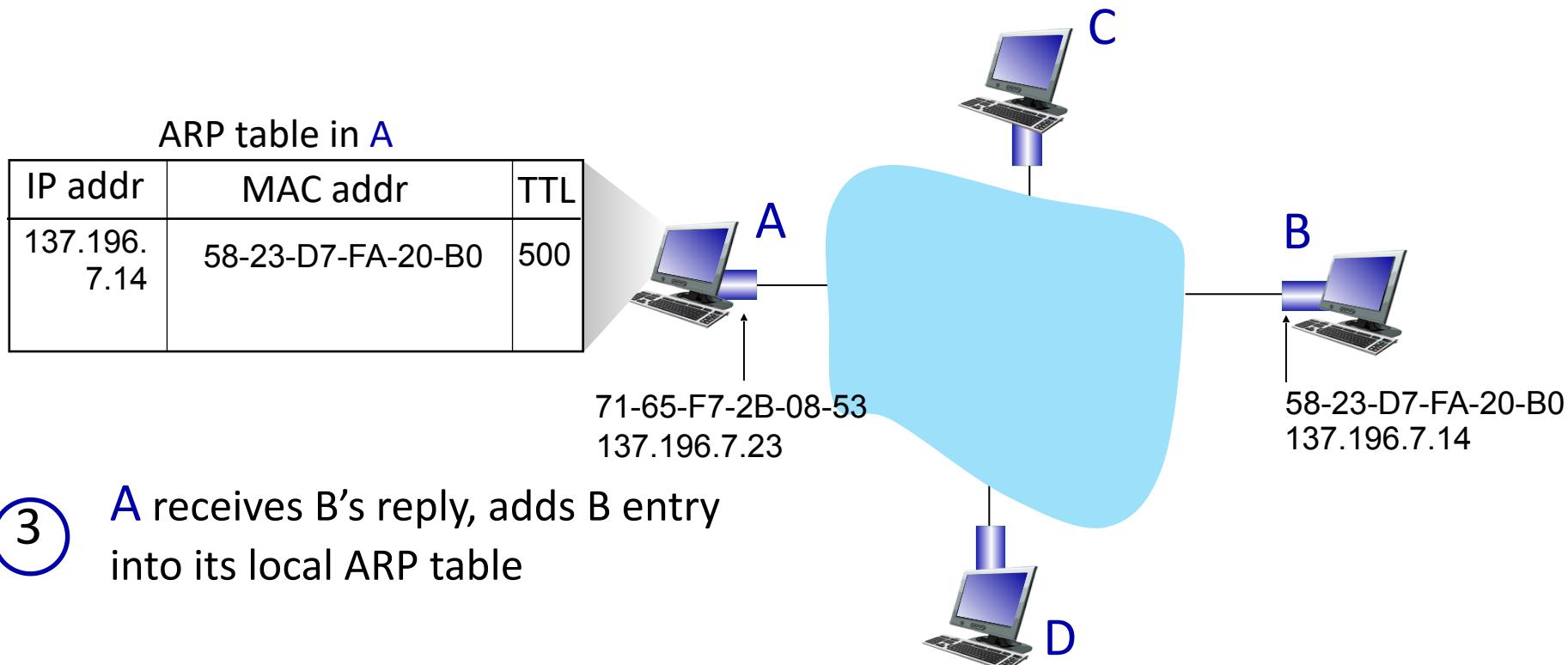
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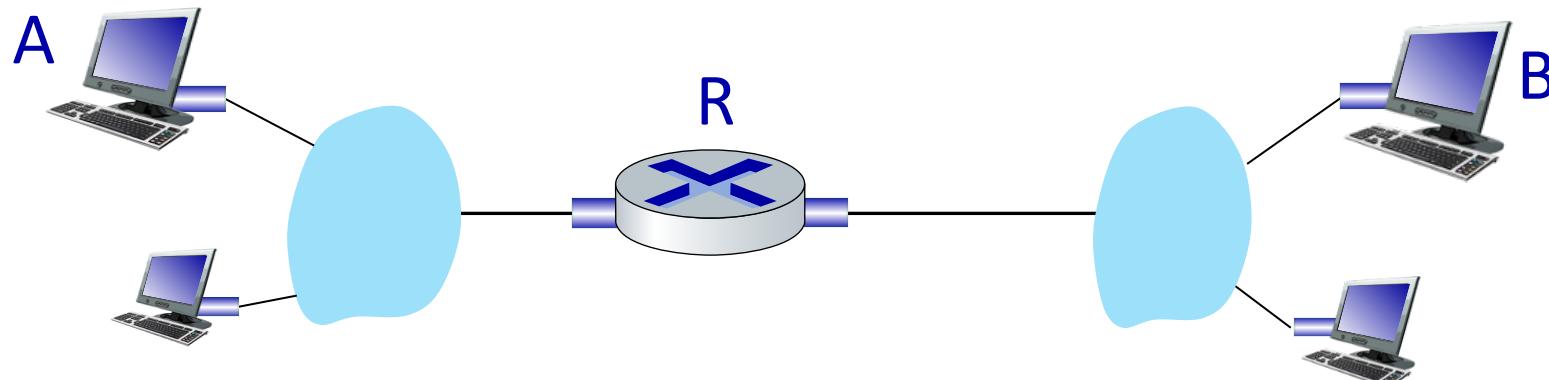
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Routing to another subnet: addressing

walkthrough: sending a datagram from *A* to *B* via *R*

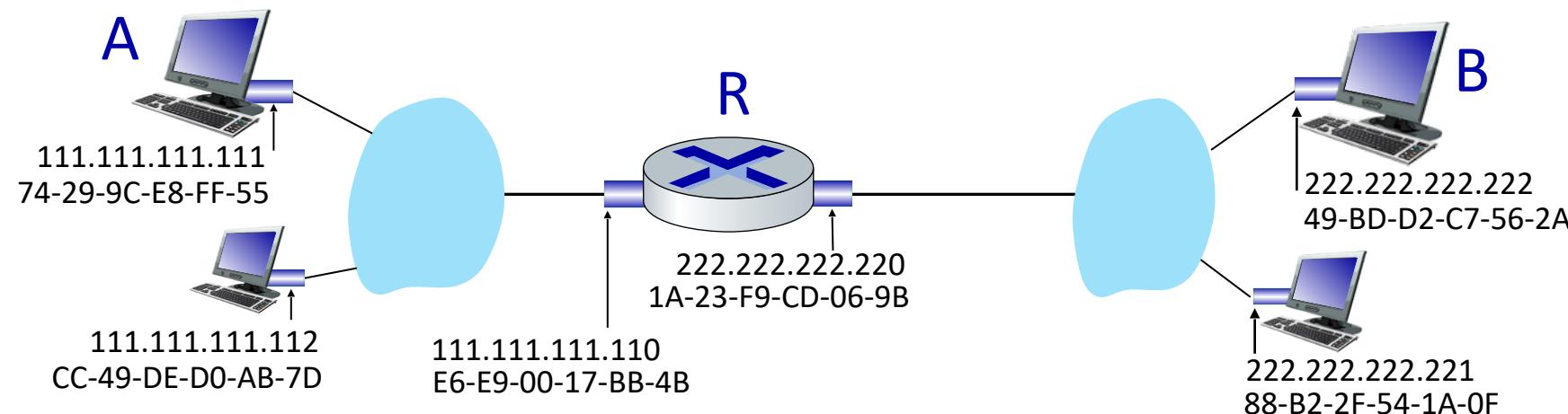
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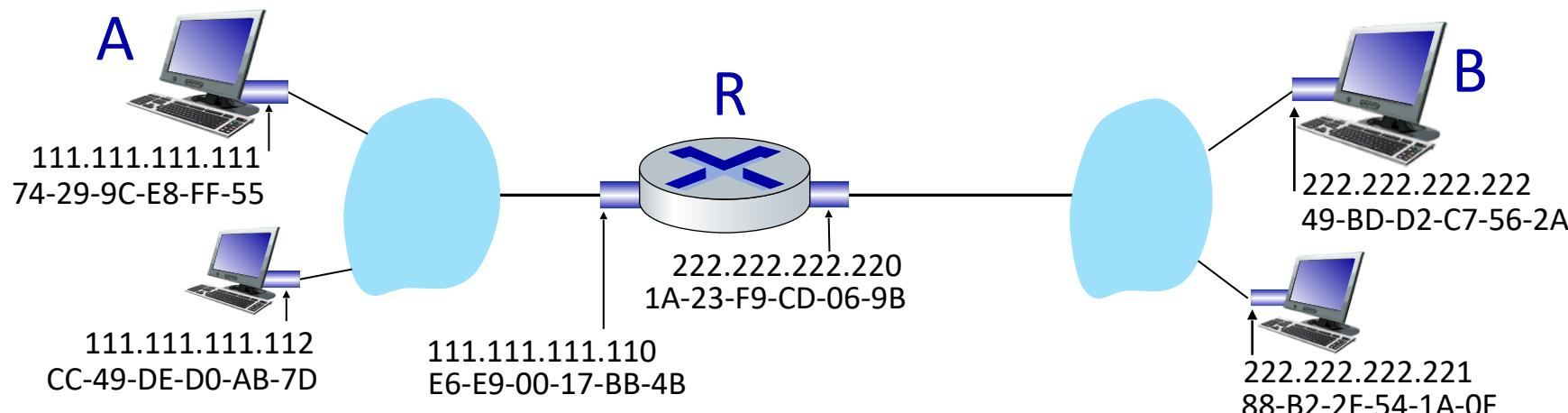
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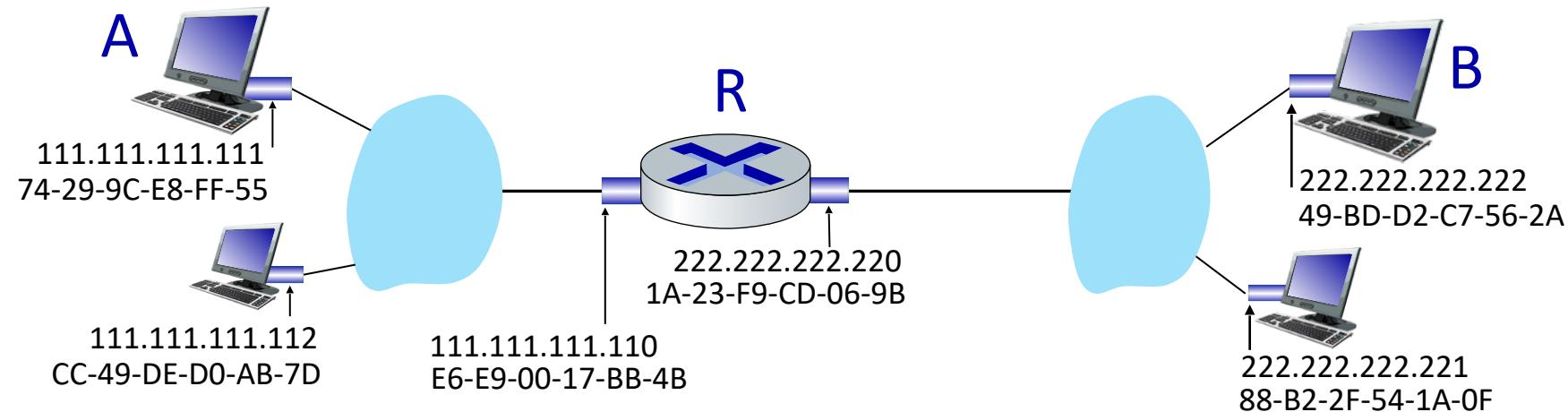
Routing to another subnet: addressing

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- focus on addressing – at IP (datagram) and MAC layer (frame) levels
- assume that:
 - A knows B's IP address
 - A knows IP address of first hop router, R (how?)
 - A knows R's MAC address (how?)

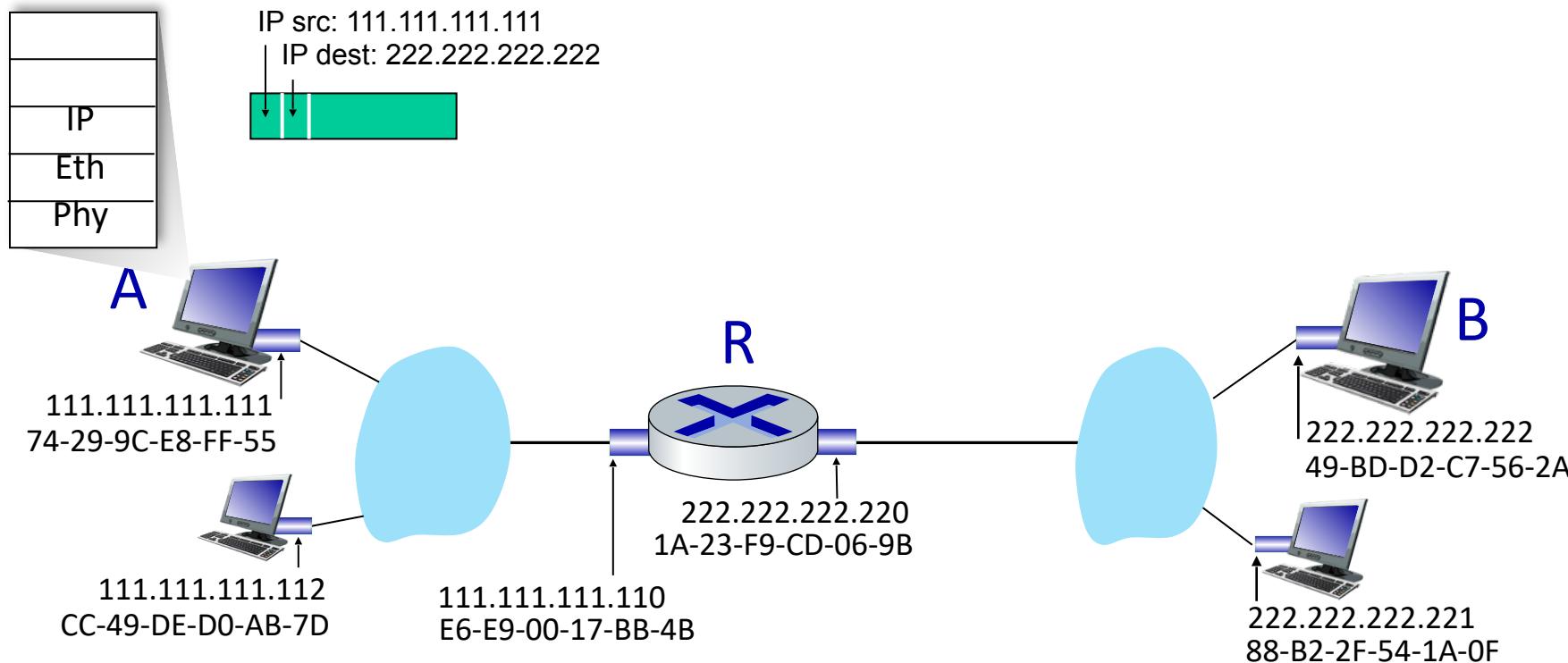


Routing to another subnet: addressing



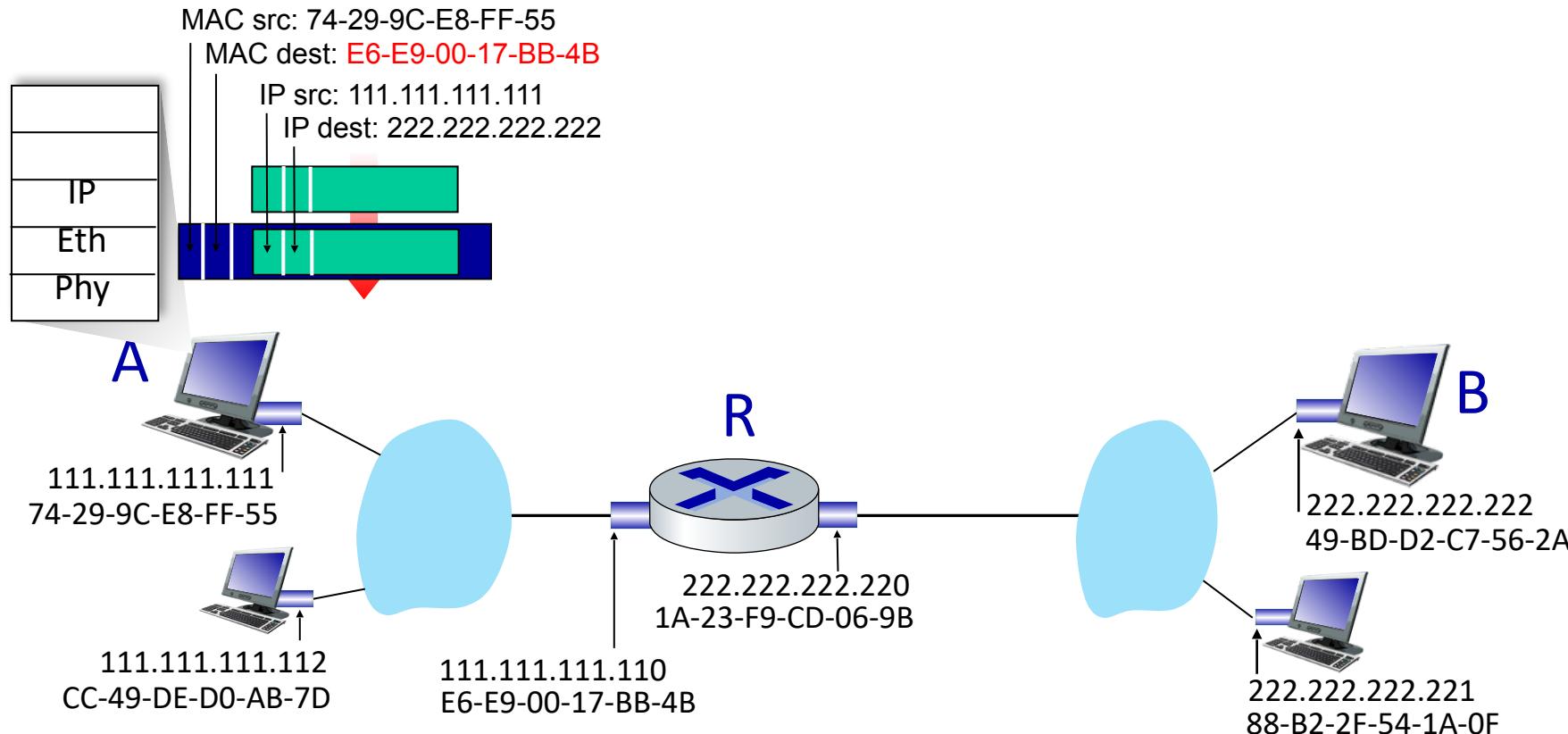
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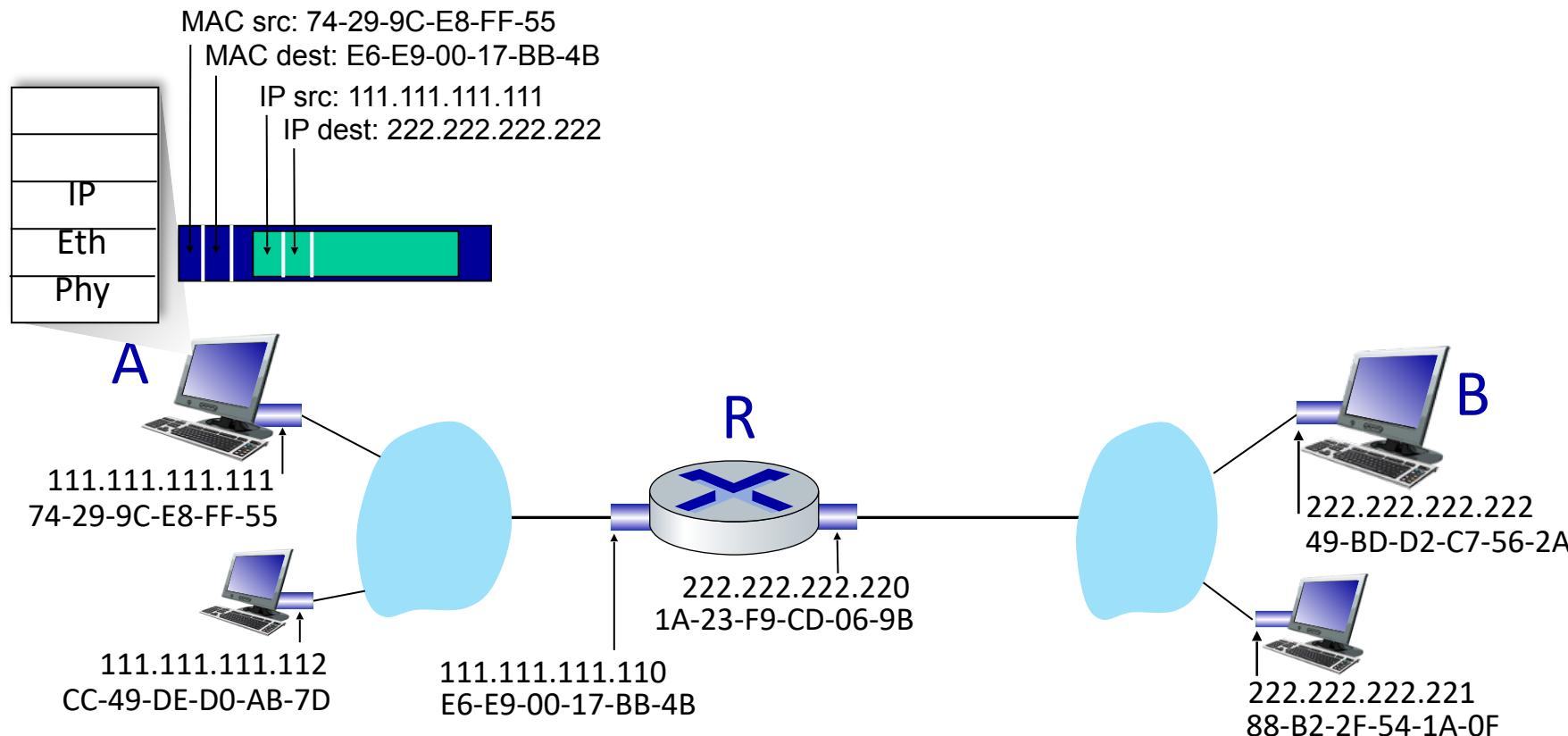
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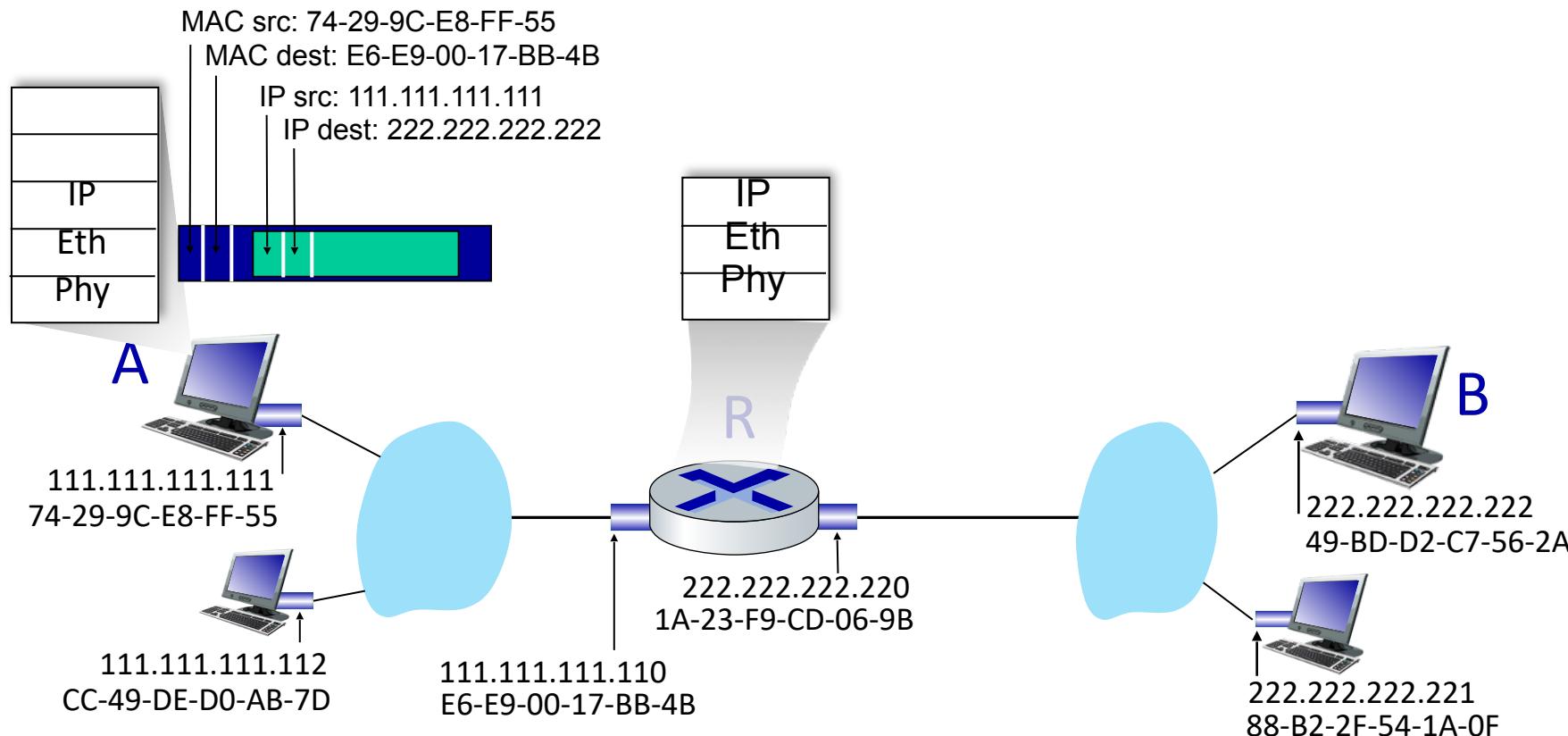
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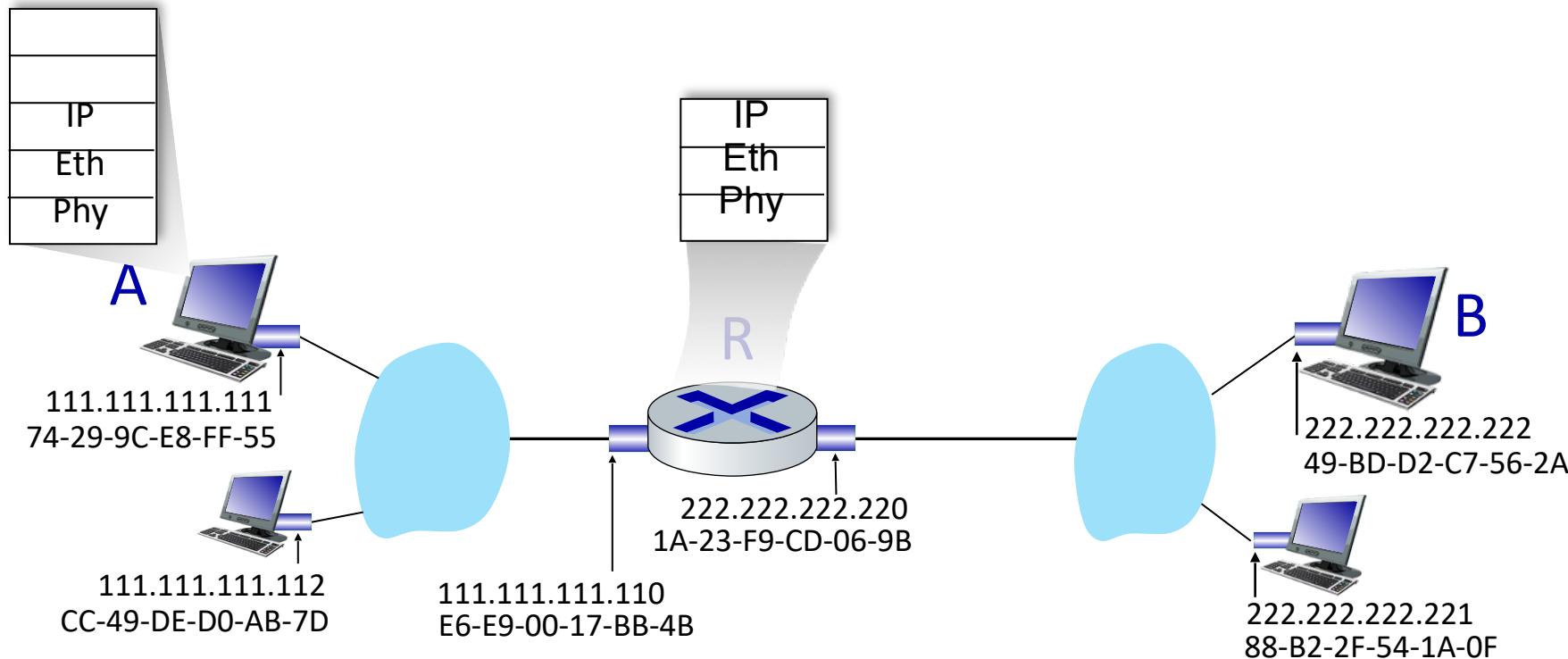
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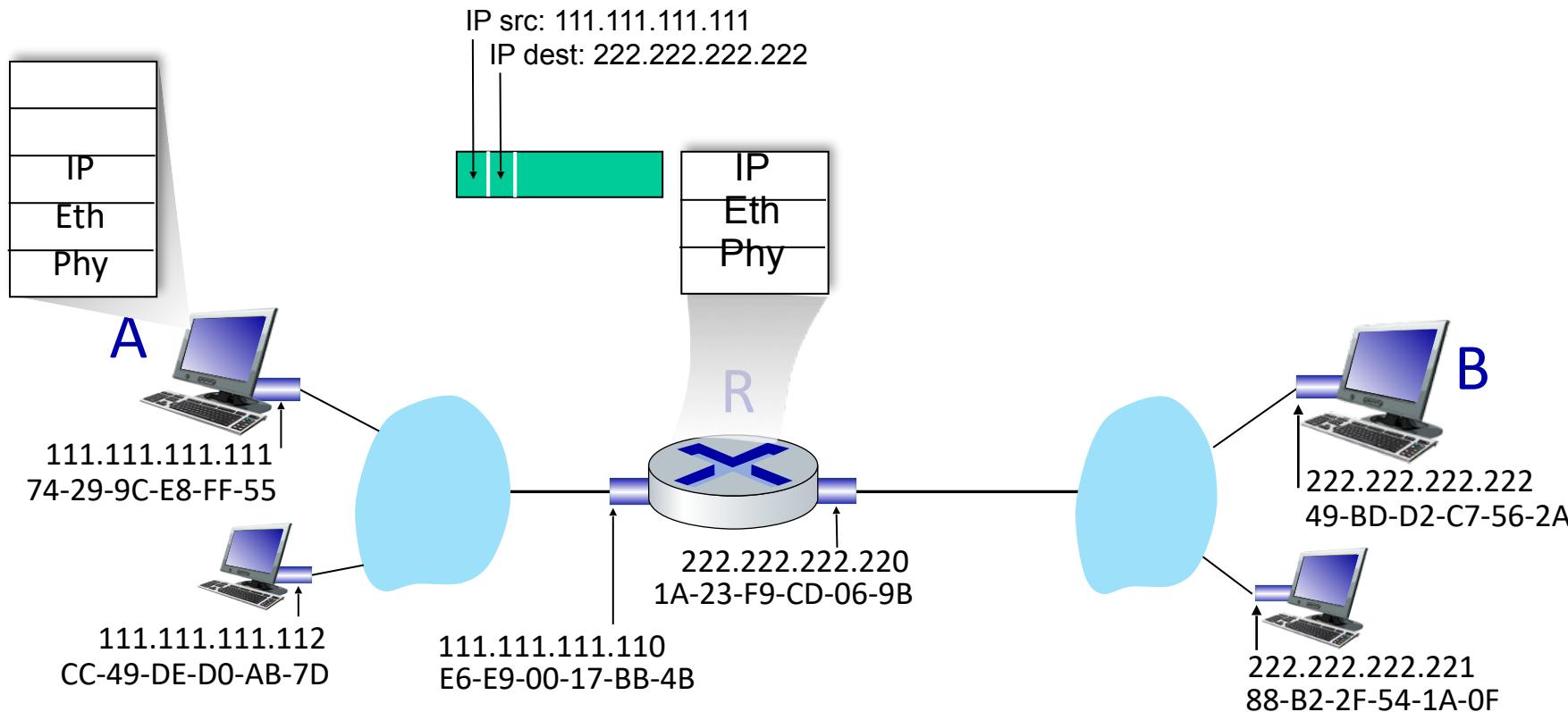
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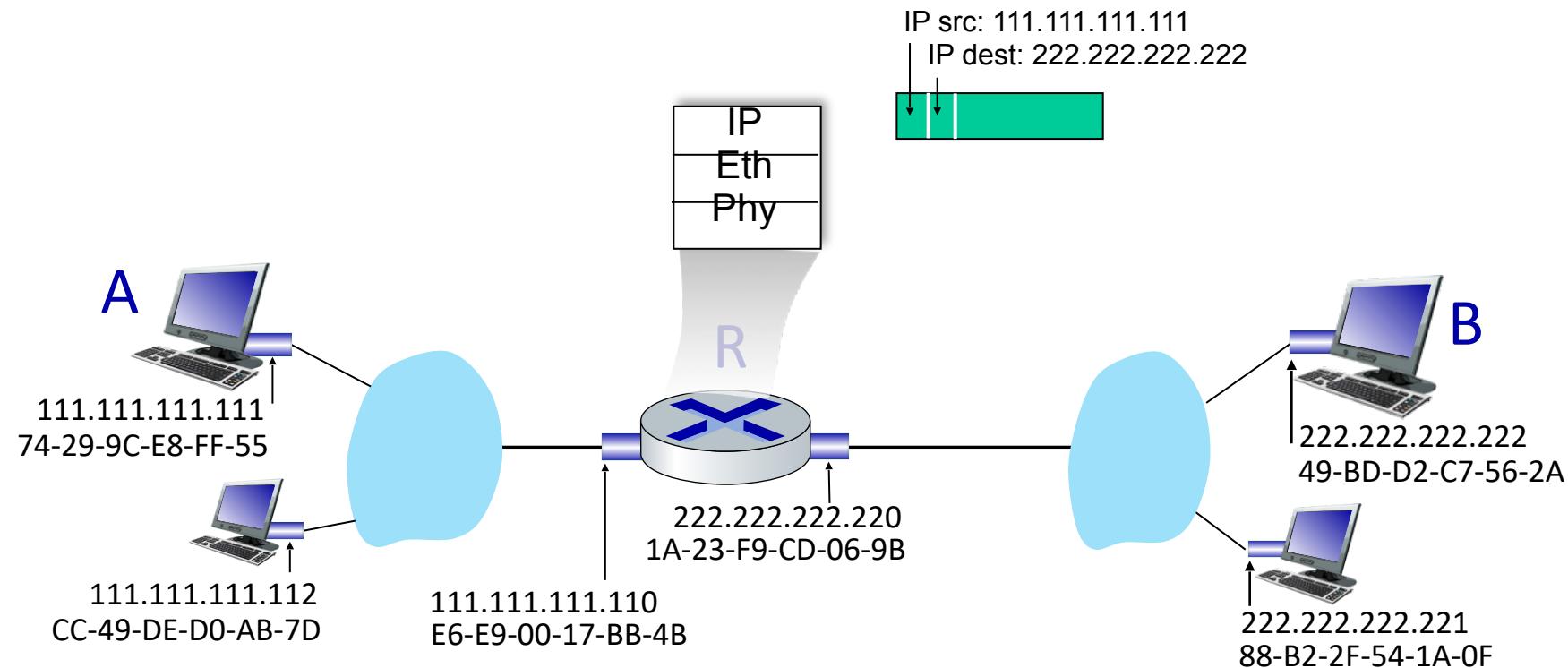


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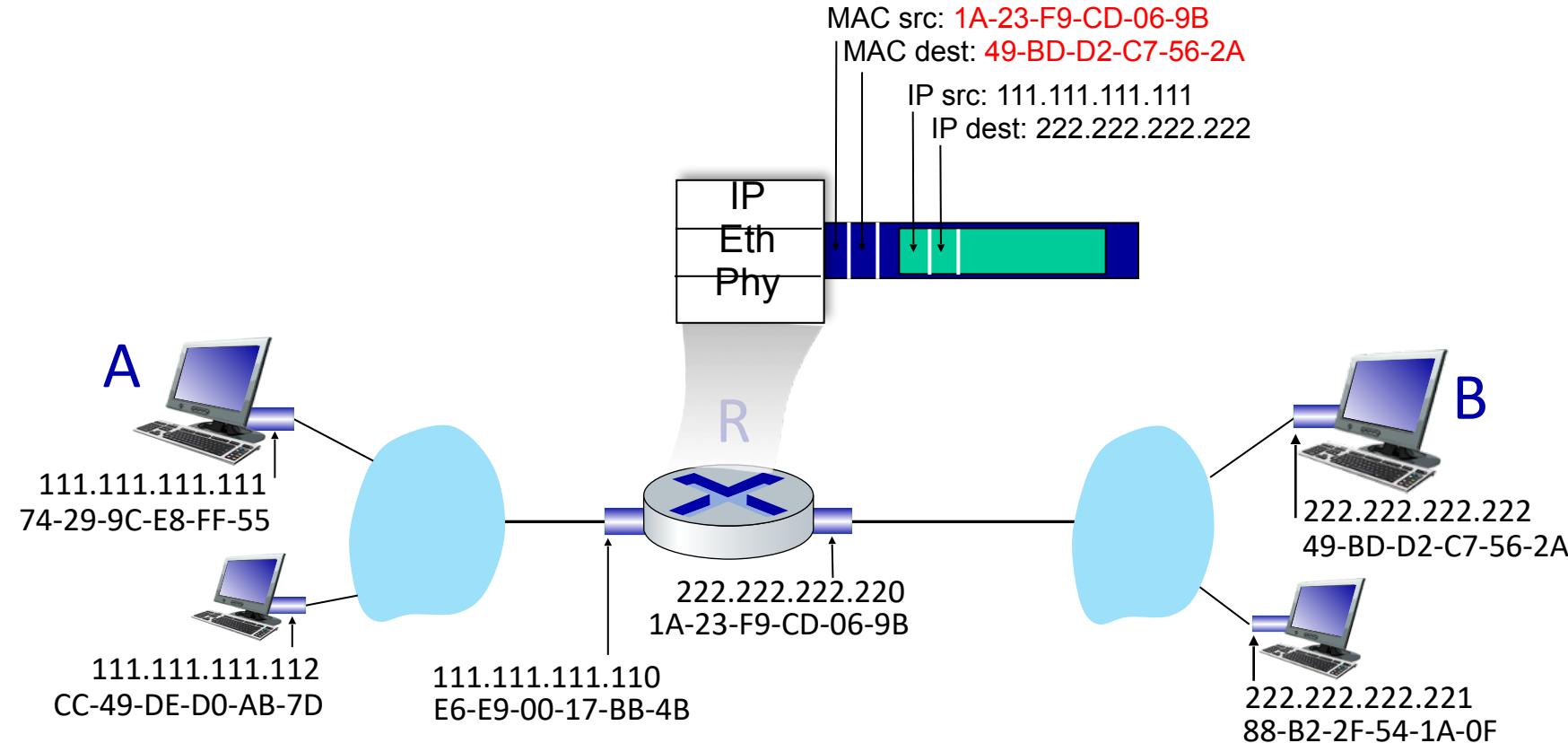


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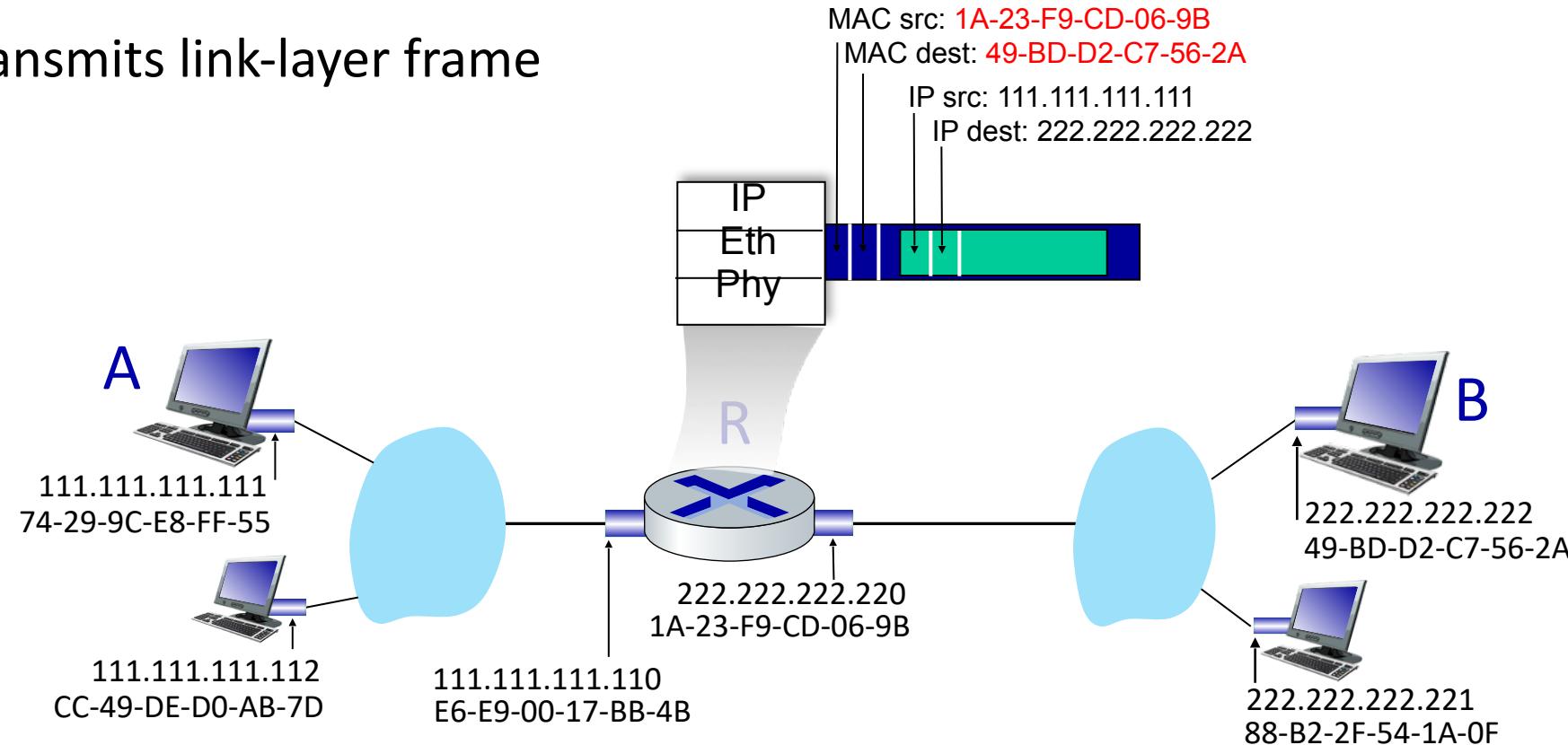
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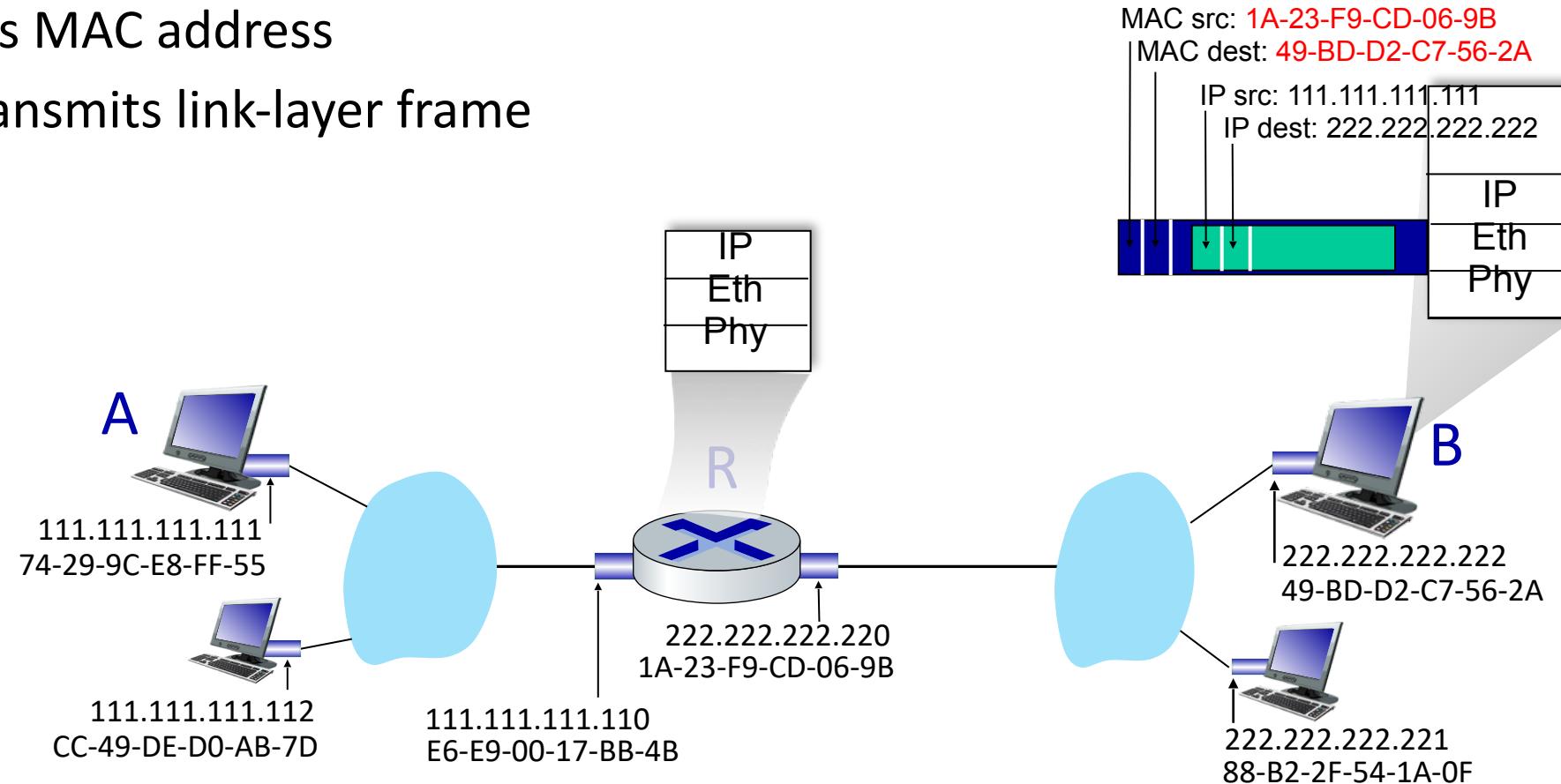
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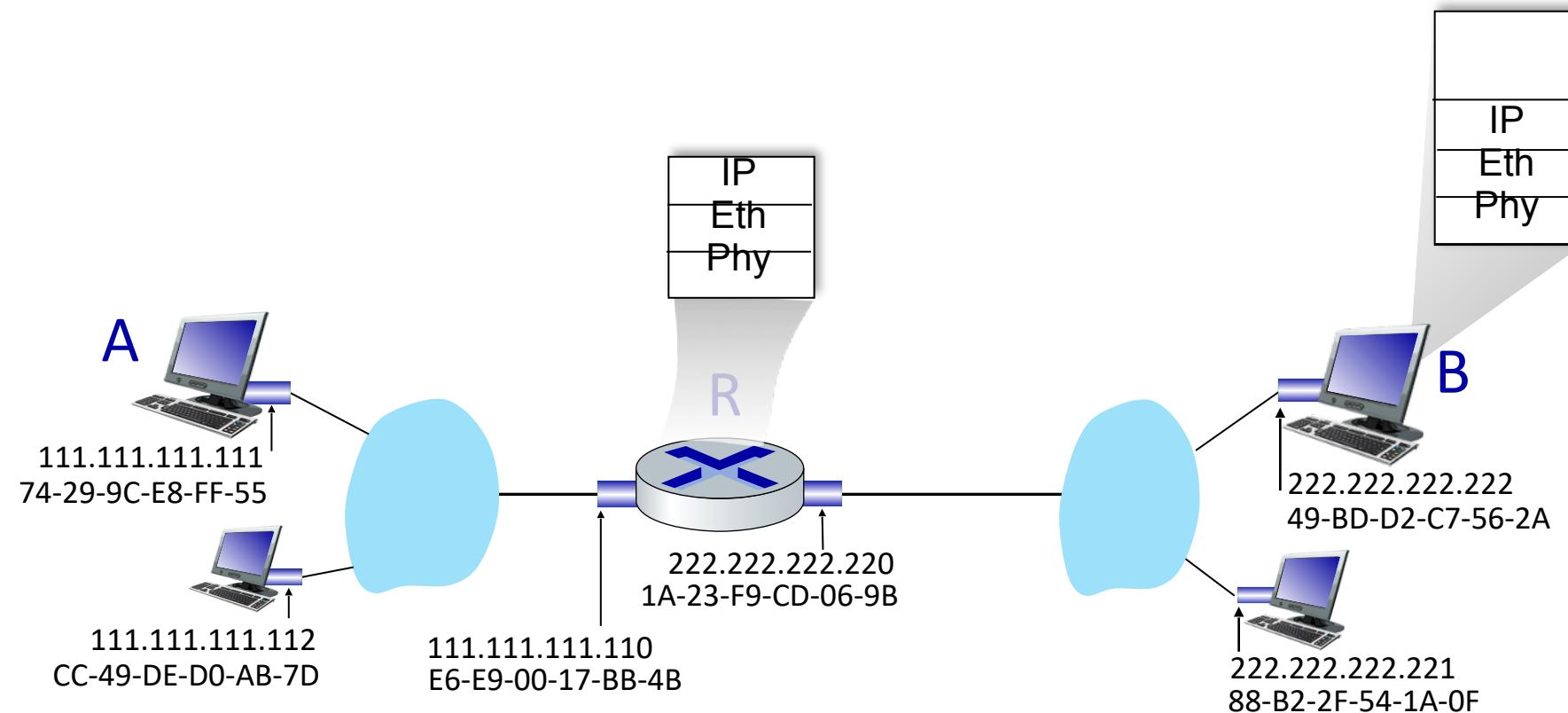
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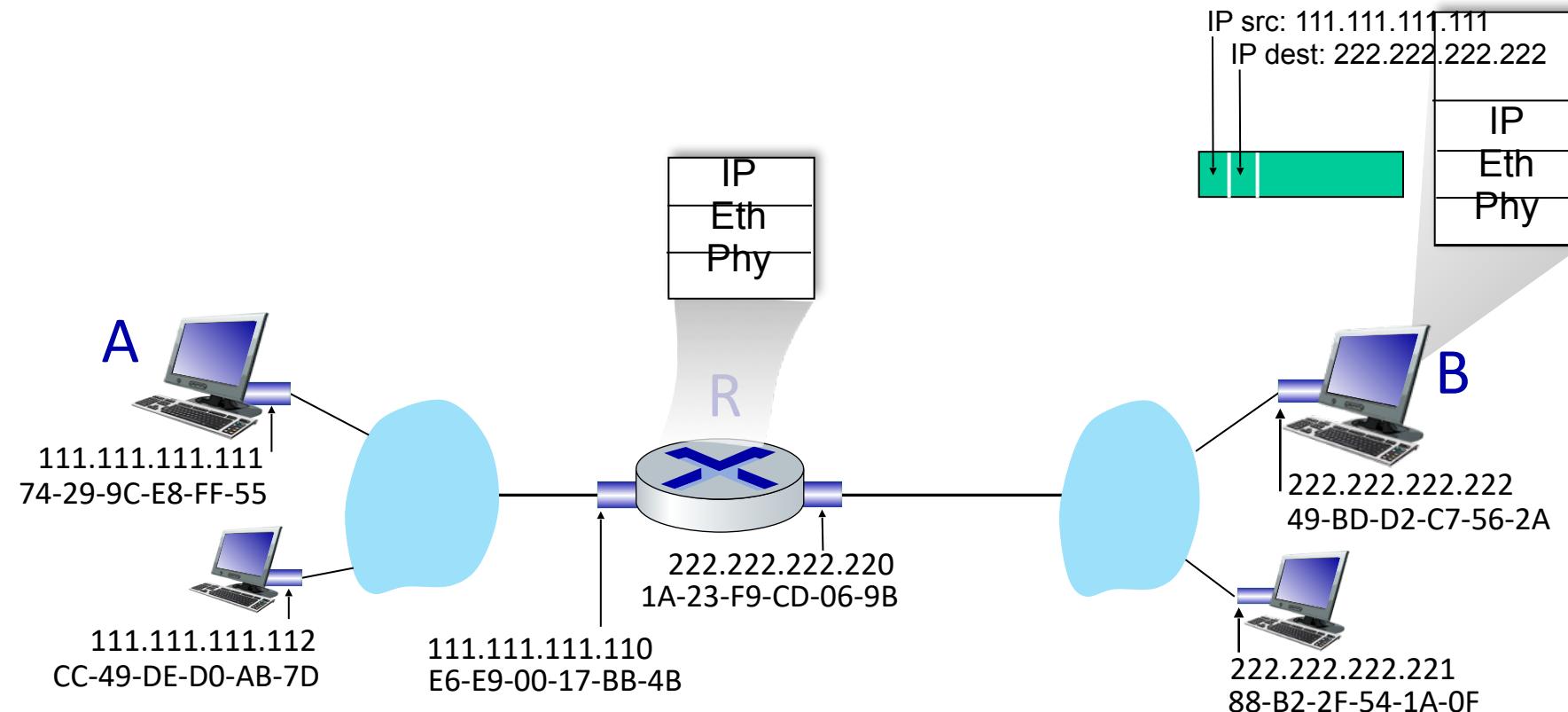
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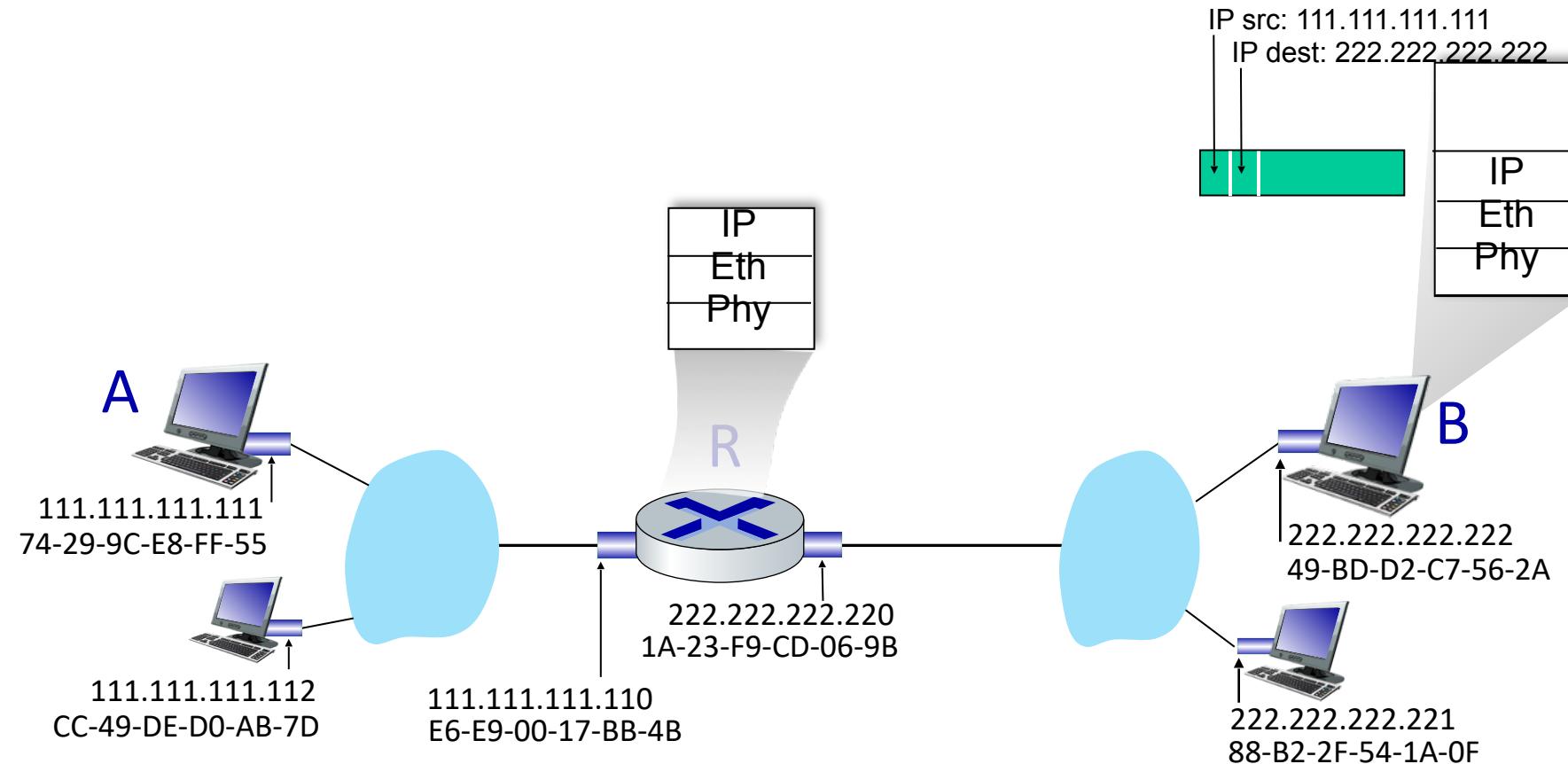
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Routing to another subnet: addressing

- B receives frame, extracts IP datagram destination B
- B passes datagram up protocol stack to IP



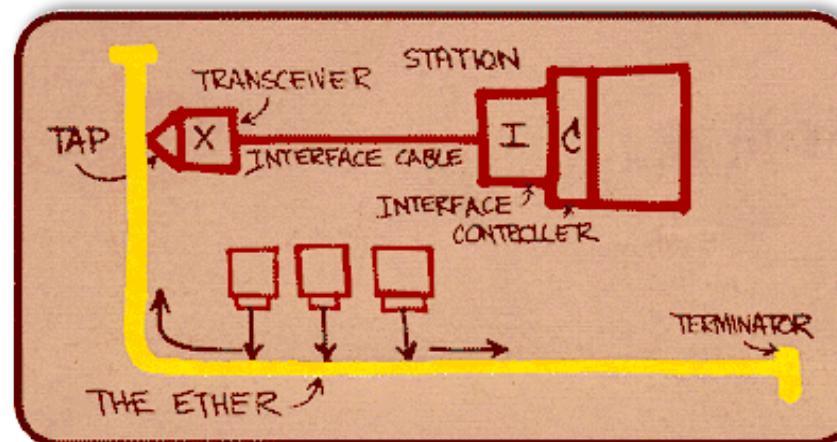
Chapter 5: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
- datacenter networking
- a day in the life of a web request

Ethernet

“dominant” wired LAN technology:

- first widely used LAN technology
- simpler, cheap
- kept up with speed race: 10 Mbps – 400 Gbps
- single chip, multiple speeds (e.g., Broadcom BCM5761)

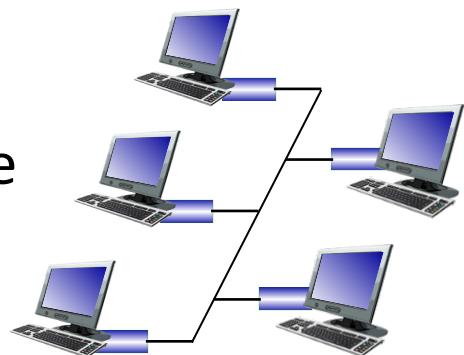


Metcalfe's Ethernet sketch

Ethernet: physical topology

- **bus:** popular through mid 90s
 - all nodes in same collision domain (can collide with each other)

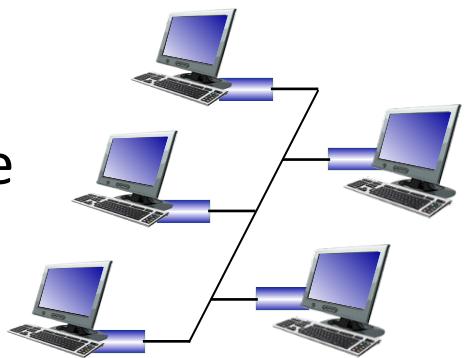
bus: coaxial cable



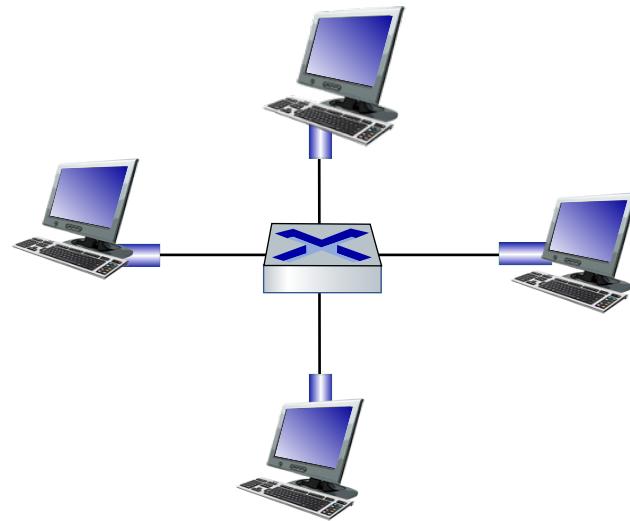
Ethernet: physical topology

- **bus:** popular through mid 90s
 - all nodes in same collision domain (can collide with each other)
- **switched:** prevails today
 - active link-layer 2 *switch* in center
 - each “spoke” runs a (separate) Ethernet protocol (nodes do not collide with each other)

bus: coaxial cable



switched



Ethernet frame structure

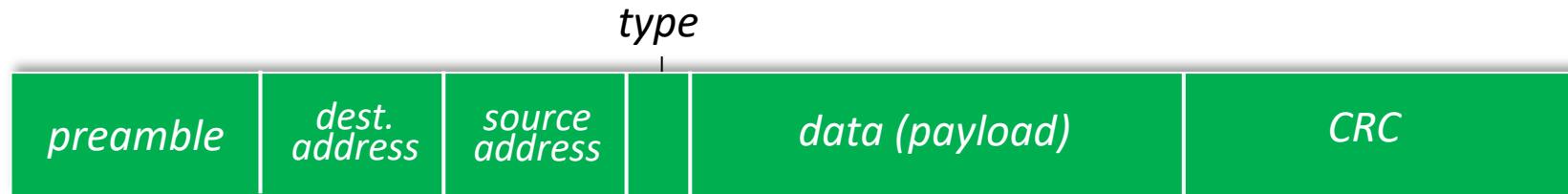
sending interface encapsulates IP datagram (or other network layer protocol packet) in **Ethernet frame**



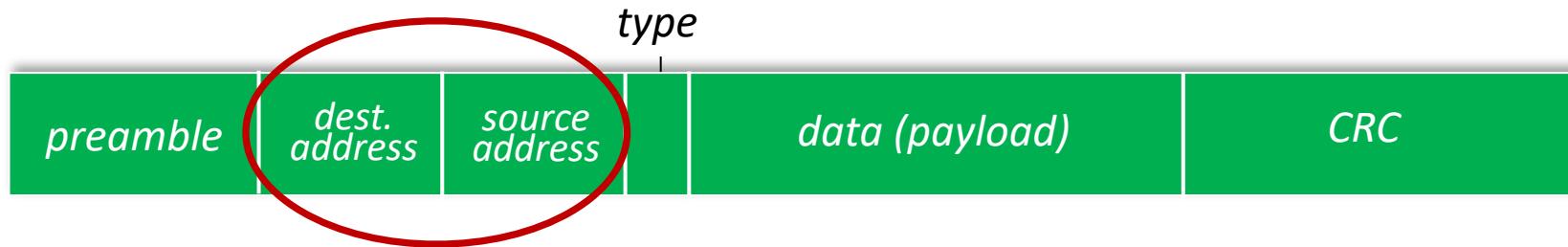
preamble:

- used to synchronize receiver, sender clock rates
- 7 bytes of 10101010 followed by one byte of 10101011

Ethernet frame structure (more)

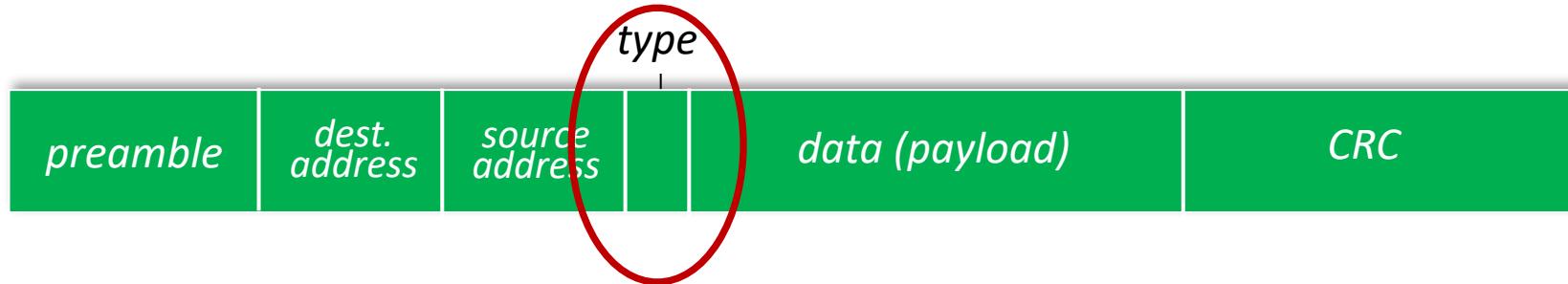


Ethernet frame structure (more)



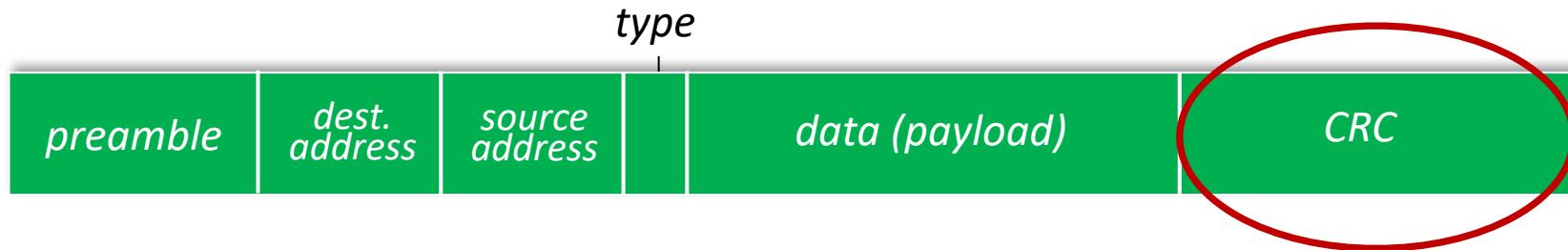
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 - used to demultiplex up at receiver
- **CRC**: cyclic redundancy check at receiver
 - error detected: frame is dropped

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Ethernet: unreliable, connectionless

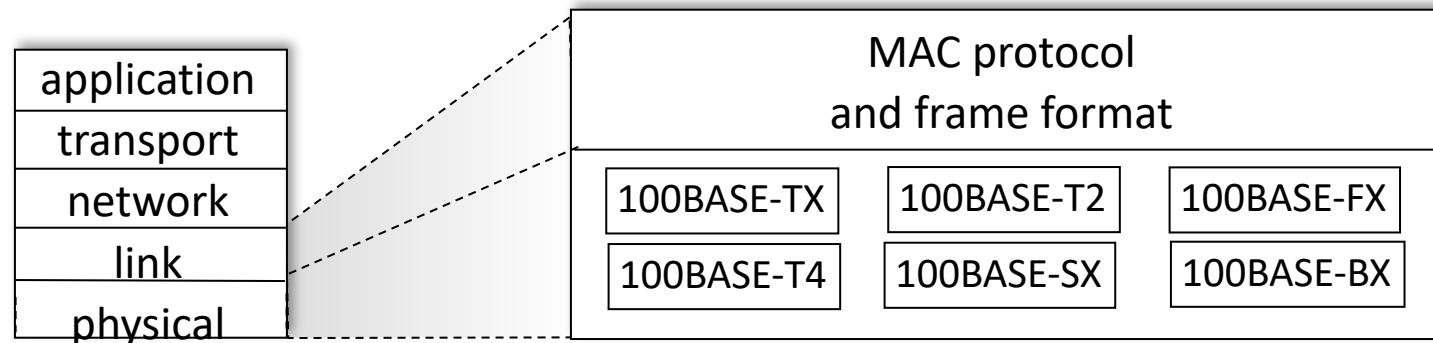
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- **unreliable:** receiving NIC doesn't send ACKs or NAKs to sending NIC
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Ethernet: unreliable, connectionless

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- Ethernet's MAC protocol: unslotted **CSMA/CD with binary backoff**

802.3 Ethernet standards: link & physical layers

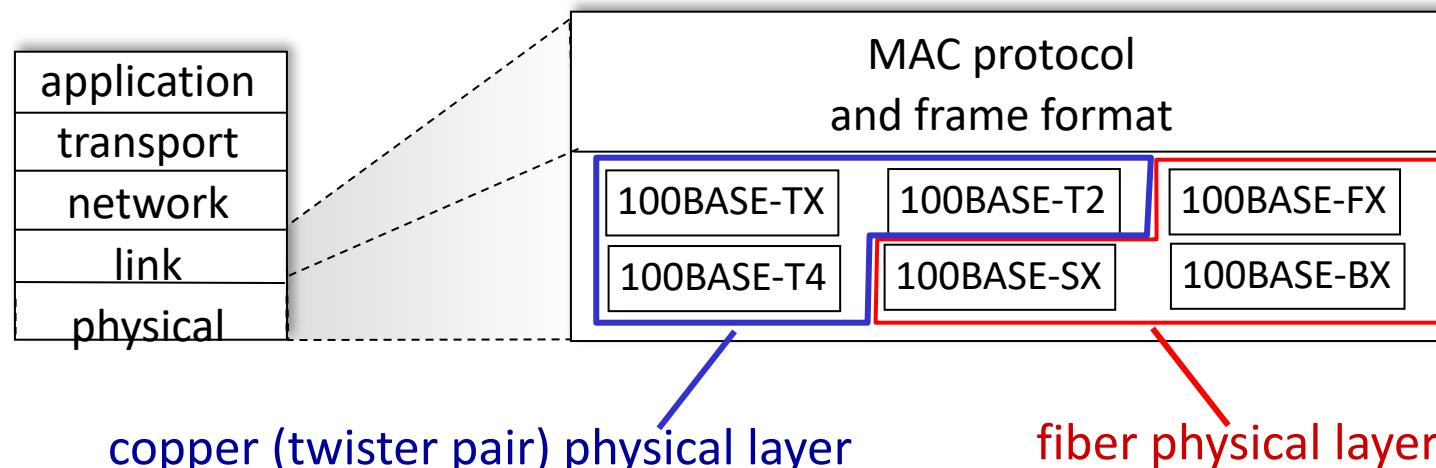
- *many* different Ethernet standards
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 - different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10 Gbps, 40 Gbps



802.3 Ethernet standards: link & physical layers

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- common MAC protocol and frame format
- different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10 Gbps, 40 Gbps
- different physical layer media: fiber, cable



Chapter 5: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
- datacenter networking
- a day in the life of a web request

Ethernet switch

- Switch is a **link-layer** device: takes an *active* role
 - store, forward Ethernet frames
 - examine incoming frame's MAC address, *selectively* forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment

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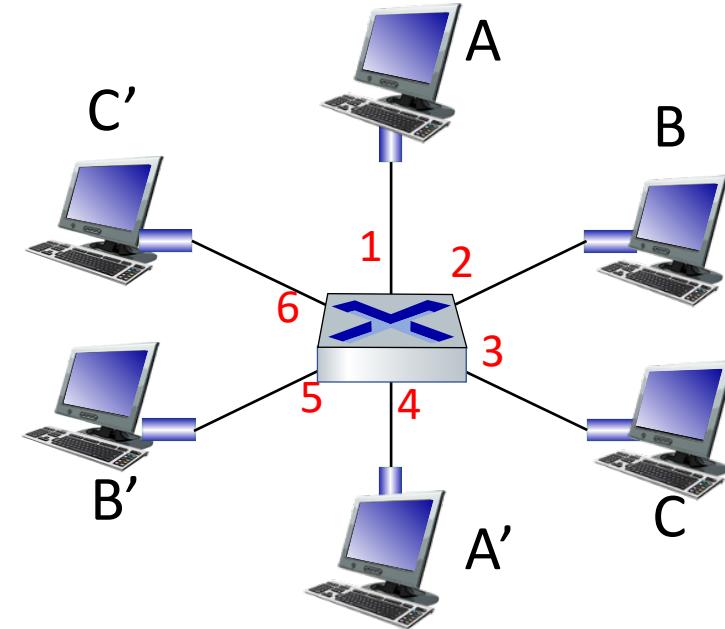
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Switch: multiple simultaneous transmissions

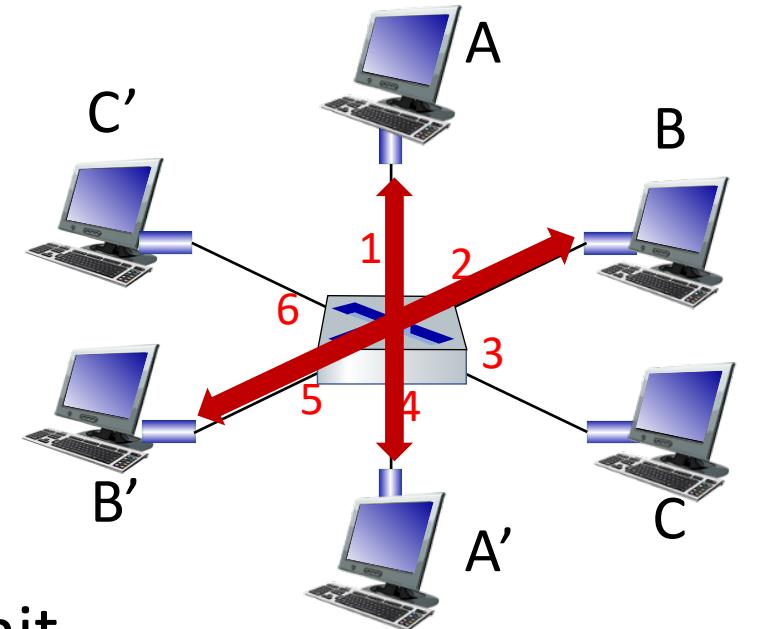
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- switches buffer packets
- Ethernet protocol used on *each* incoming link, so:
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switch with six
interfaces (1,2,3,4,5,6)

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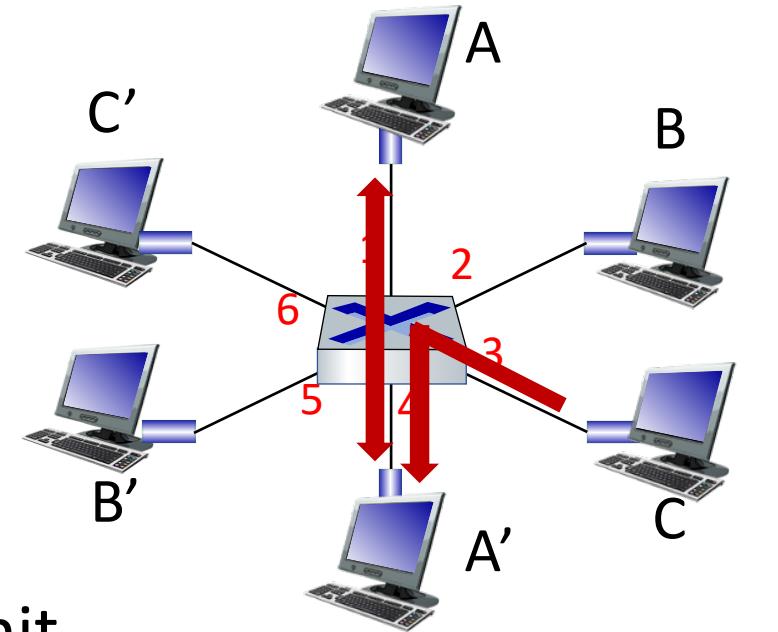
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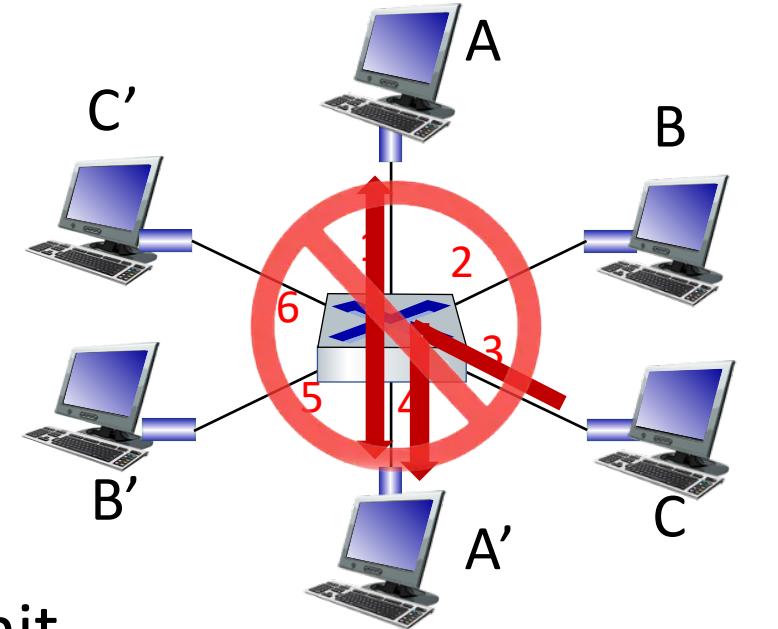
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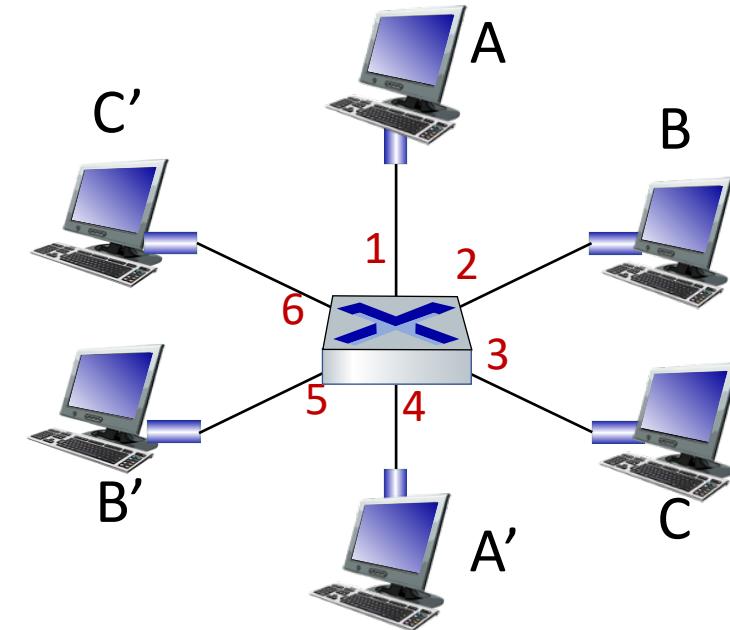
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Switch forwarding table

Q: how does switch know A' reachable via interface 4, B' reachable via interface 5?

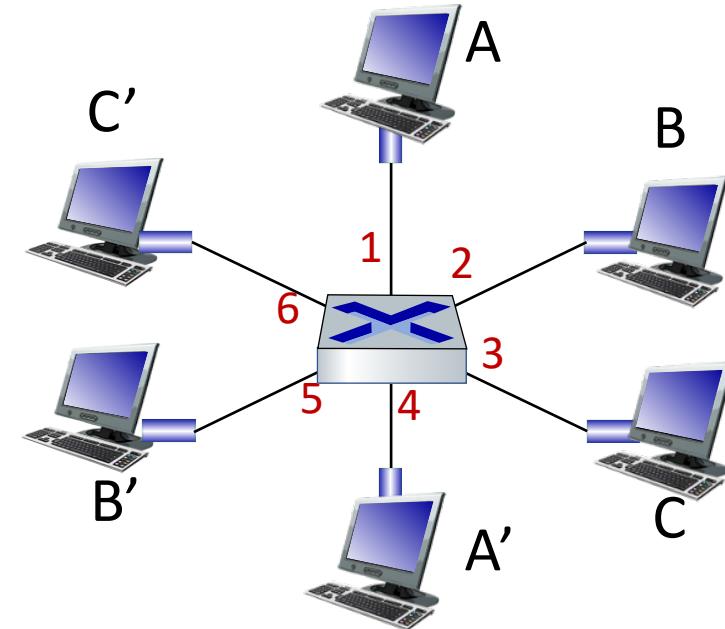


Switch forwarding table

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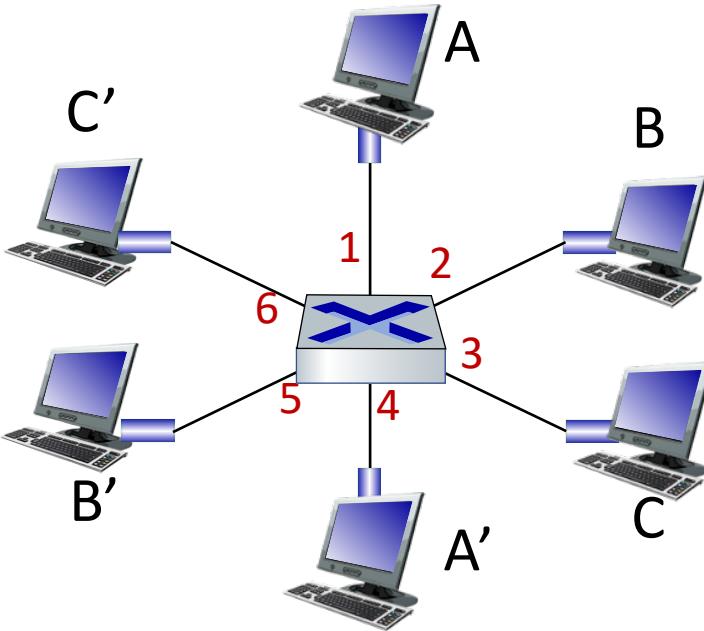


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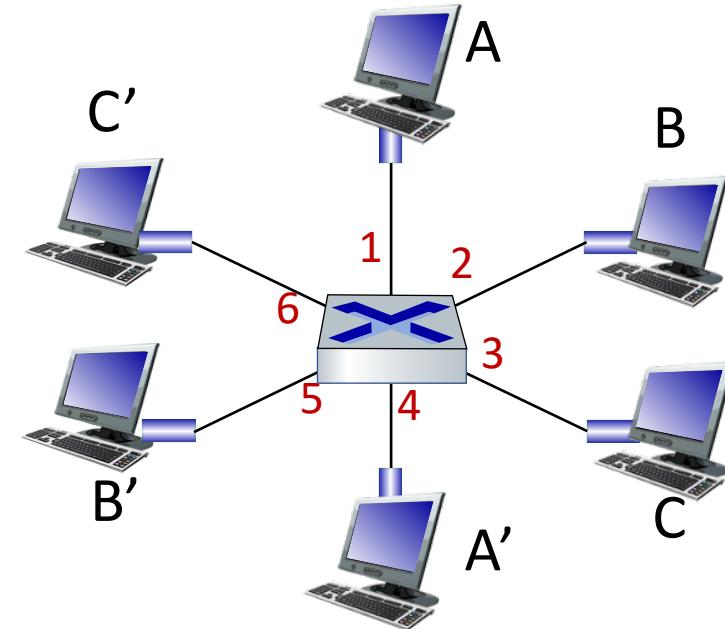


Q: how are entries created, maintained in switch table?

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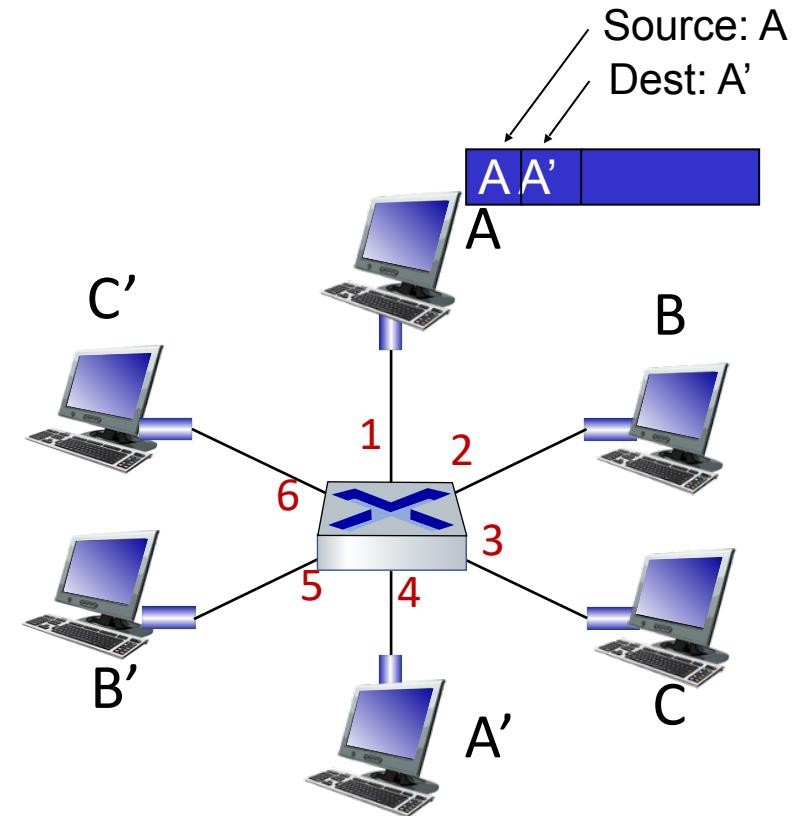
Switch: self-learning

- switch *learns* which hosts can be reached through which interfaces



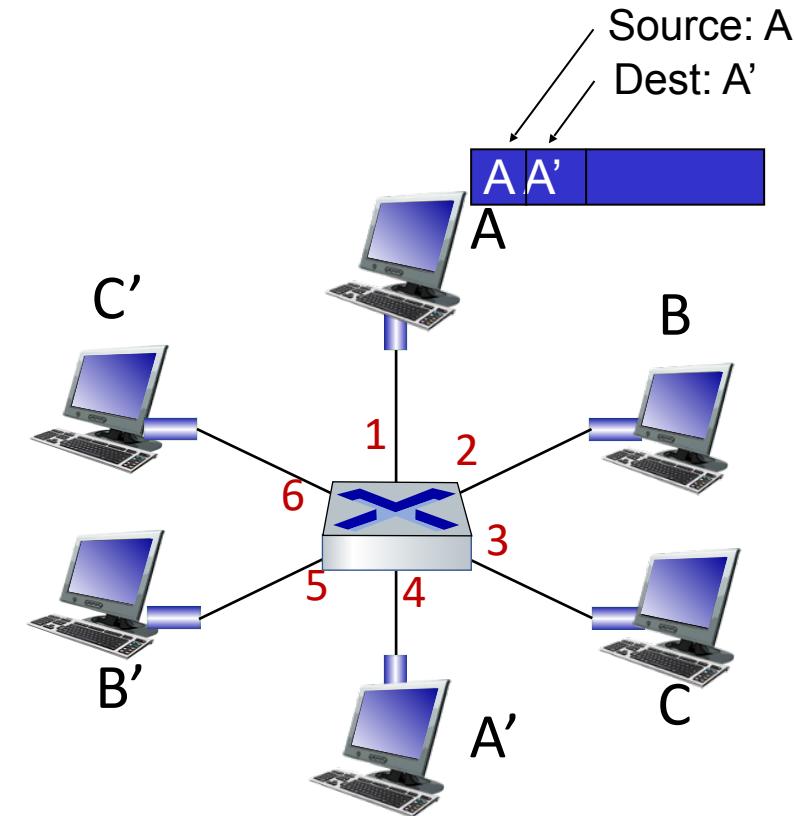
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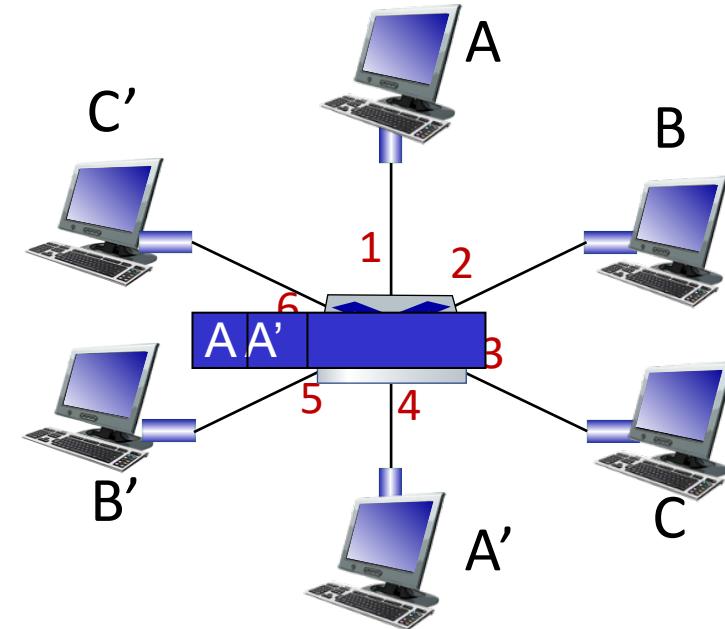


MAC addr	interface	TTL

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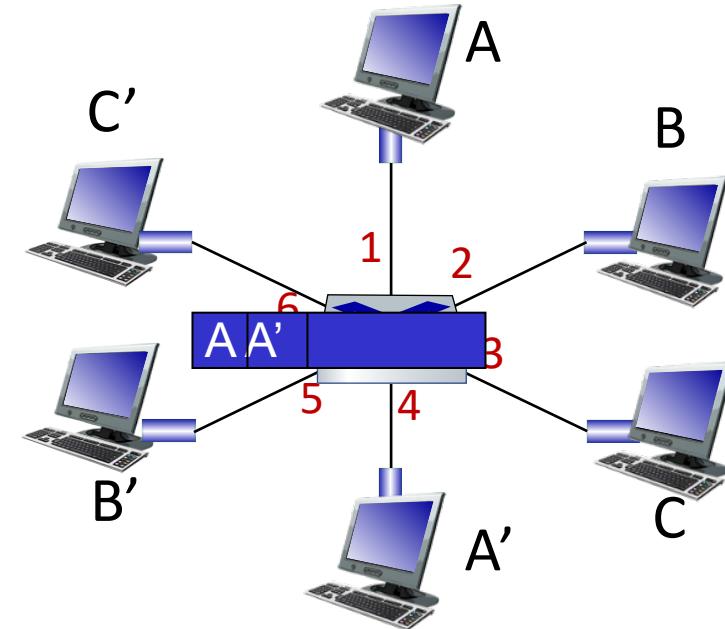


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 - when frame received, switch “learns” location of sender: incoming LAN segment
 - records sender/location pair in switch table



MAC addr	interface	TTL
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Switch: frame filtering/forwarding

when frame received at switch:

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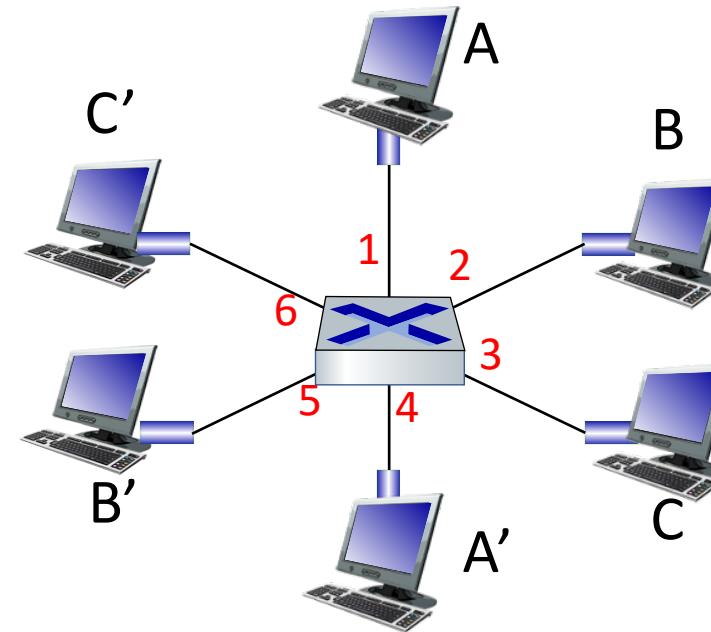
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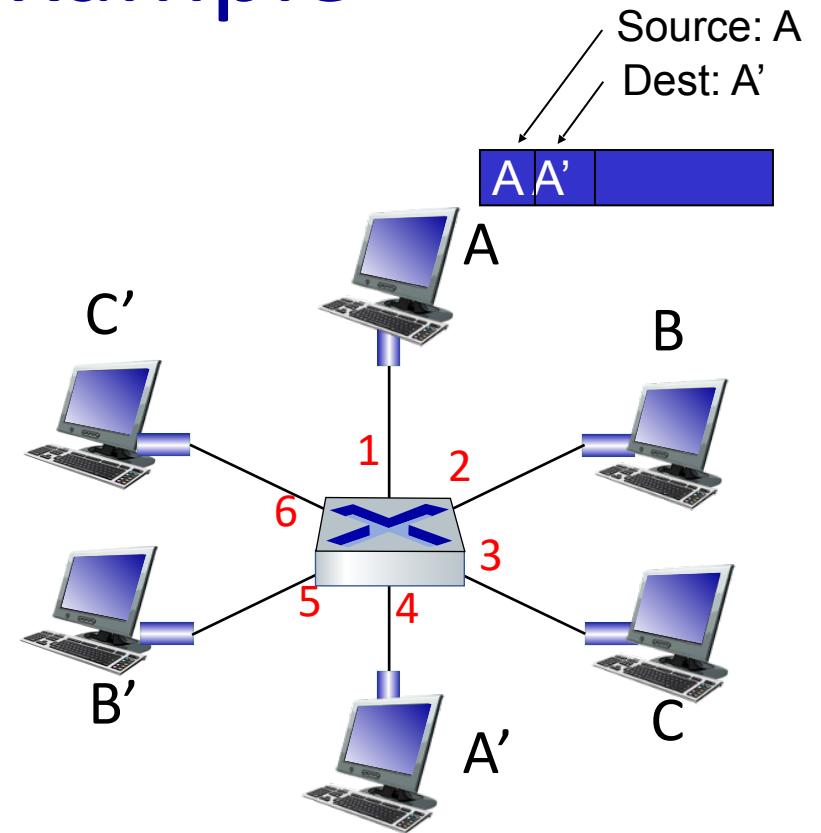
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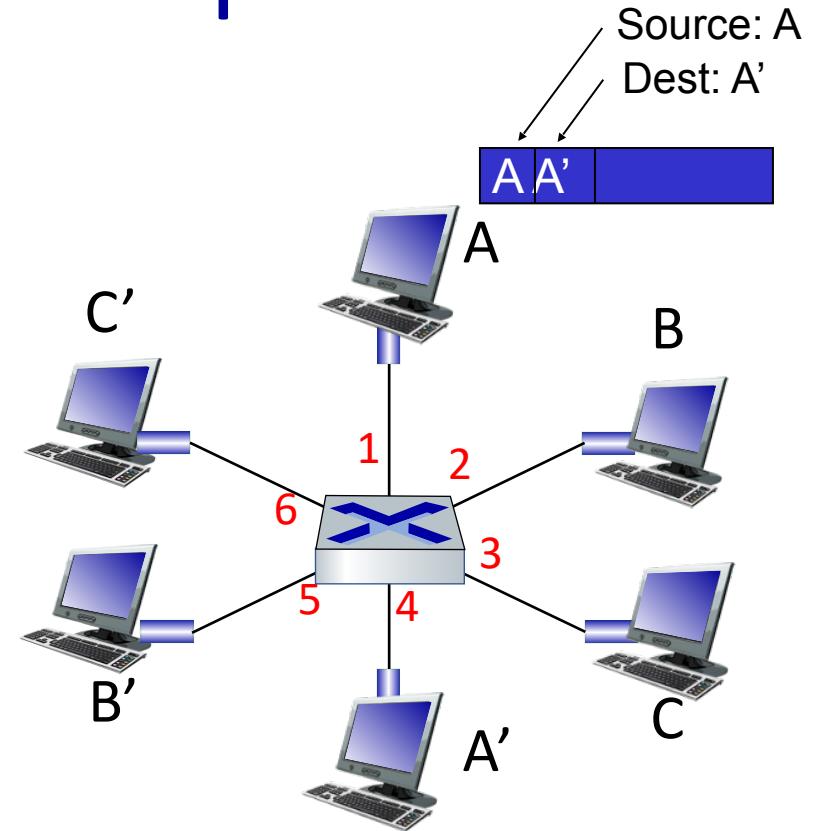
Self-learning, forwarding: example



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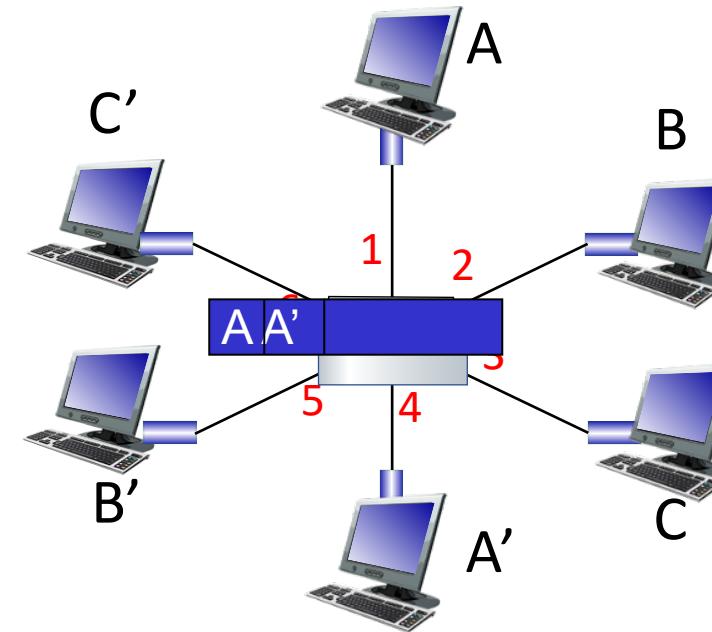


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Self-learning, forwarding: example

- frame destination, A', location unknown:

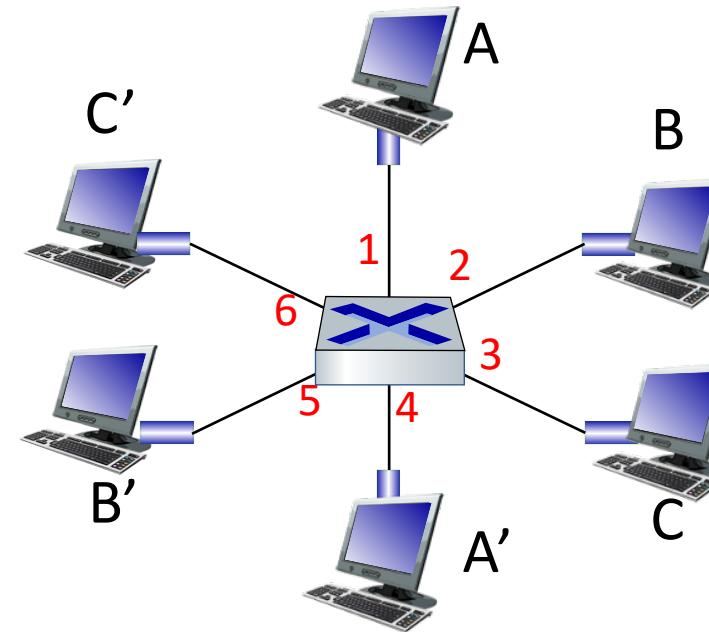


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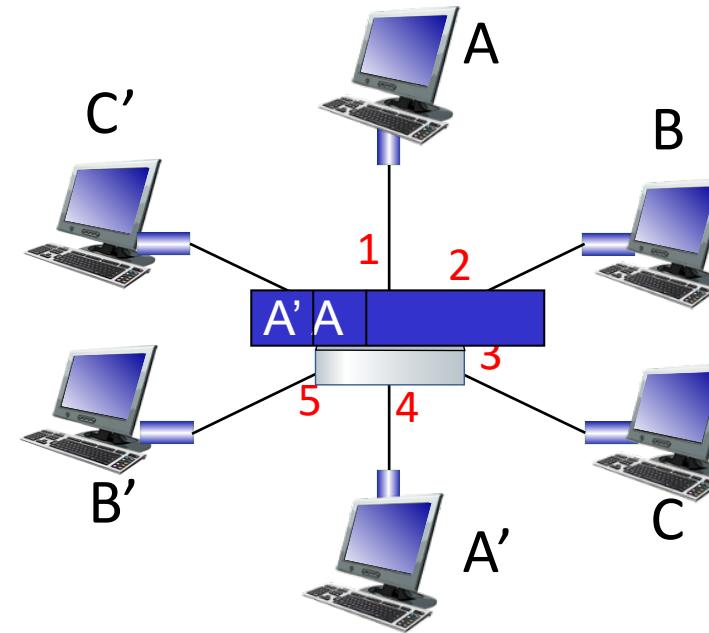


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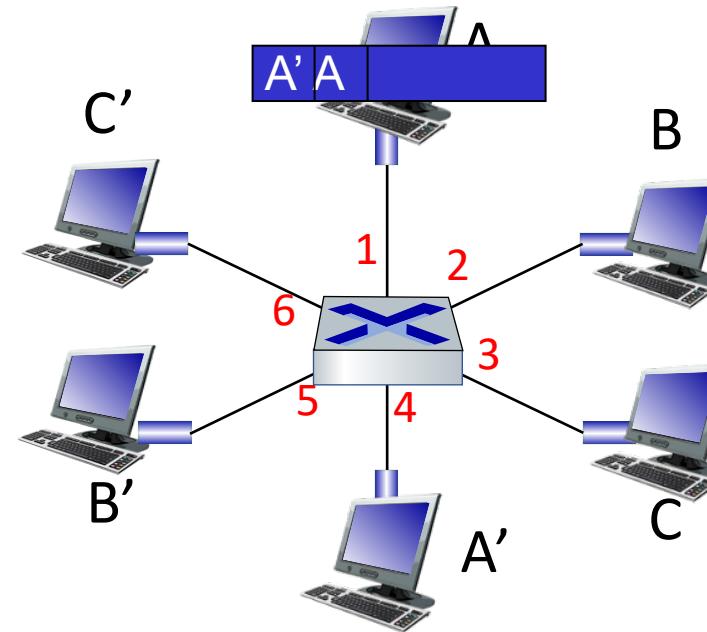


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Self-learning, forwarding: example

- frame destination, A', location unknown: **flood**
- destination A location known: **selectively send on just one link**

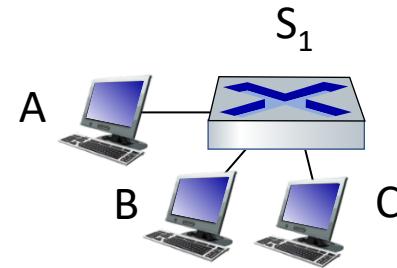


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A'	4	60

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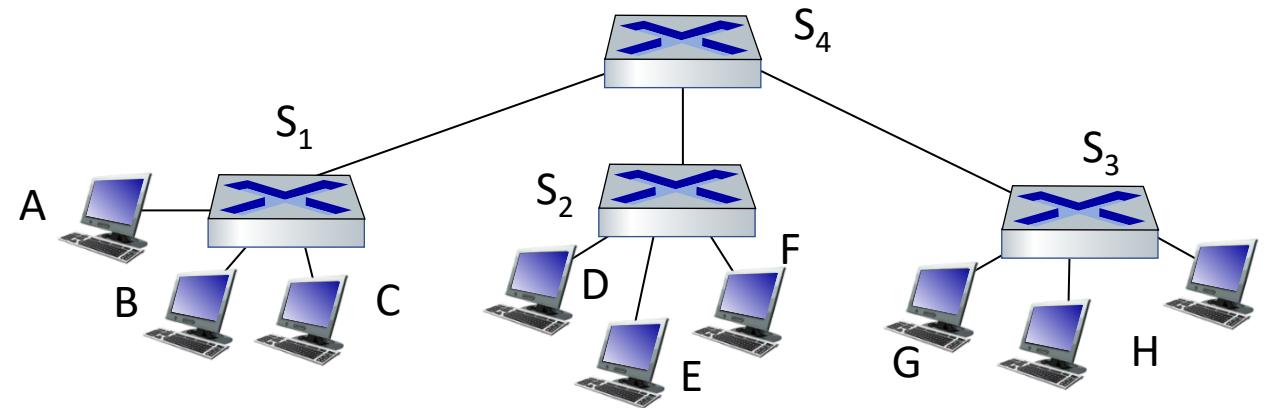
Interconnecting switches

self-learning switches can be connected together:



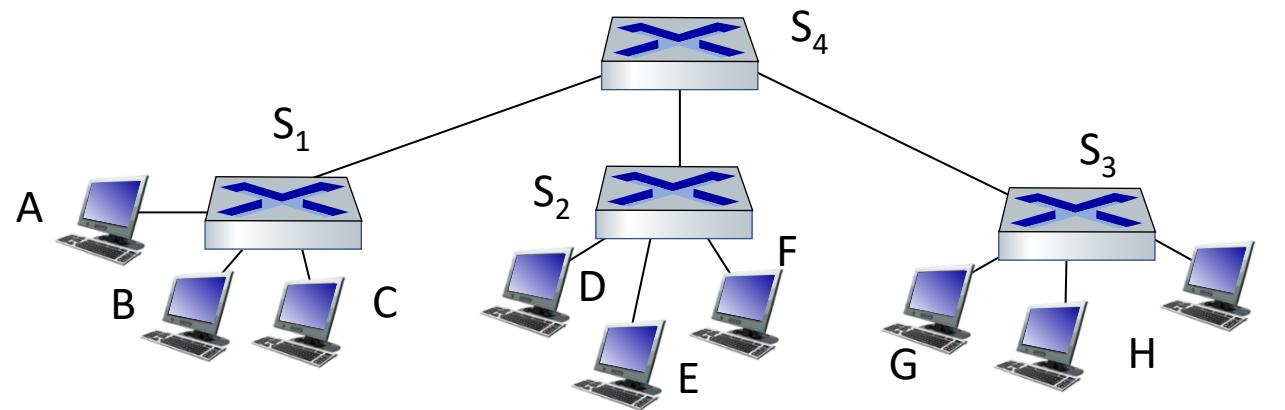
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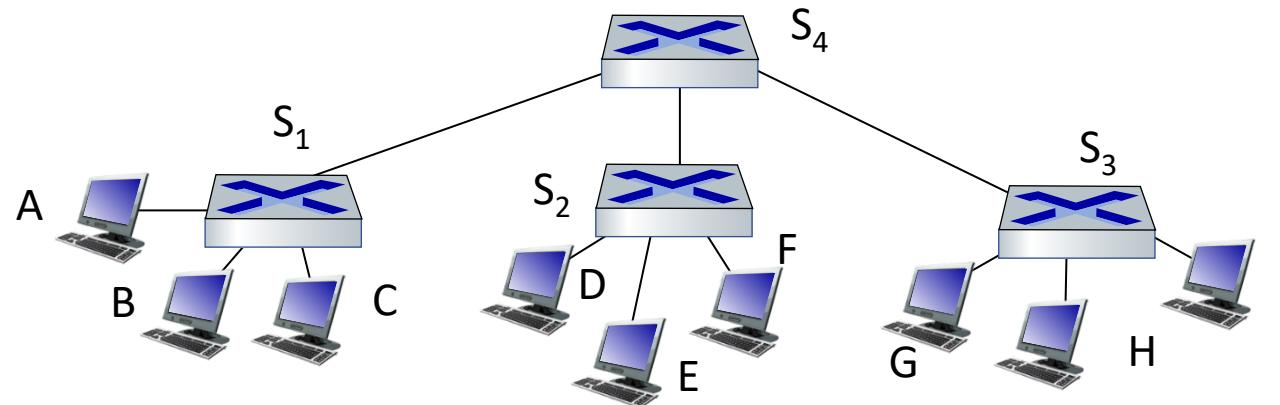


Q: sending from A to G - how does S_1 know to forward frame destined to G via S_4 and S_3 ?

- **A:** self learning! (works exactly the same as in single-switch case!)

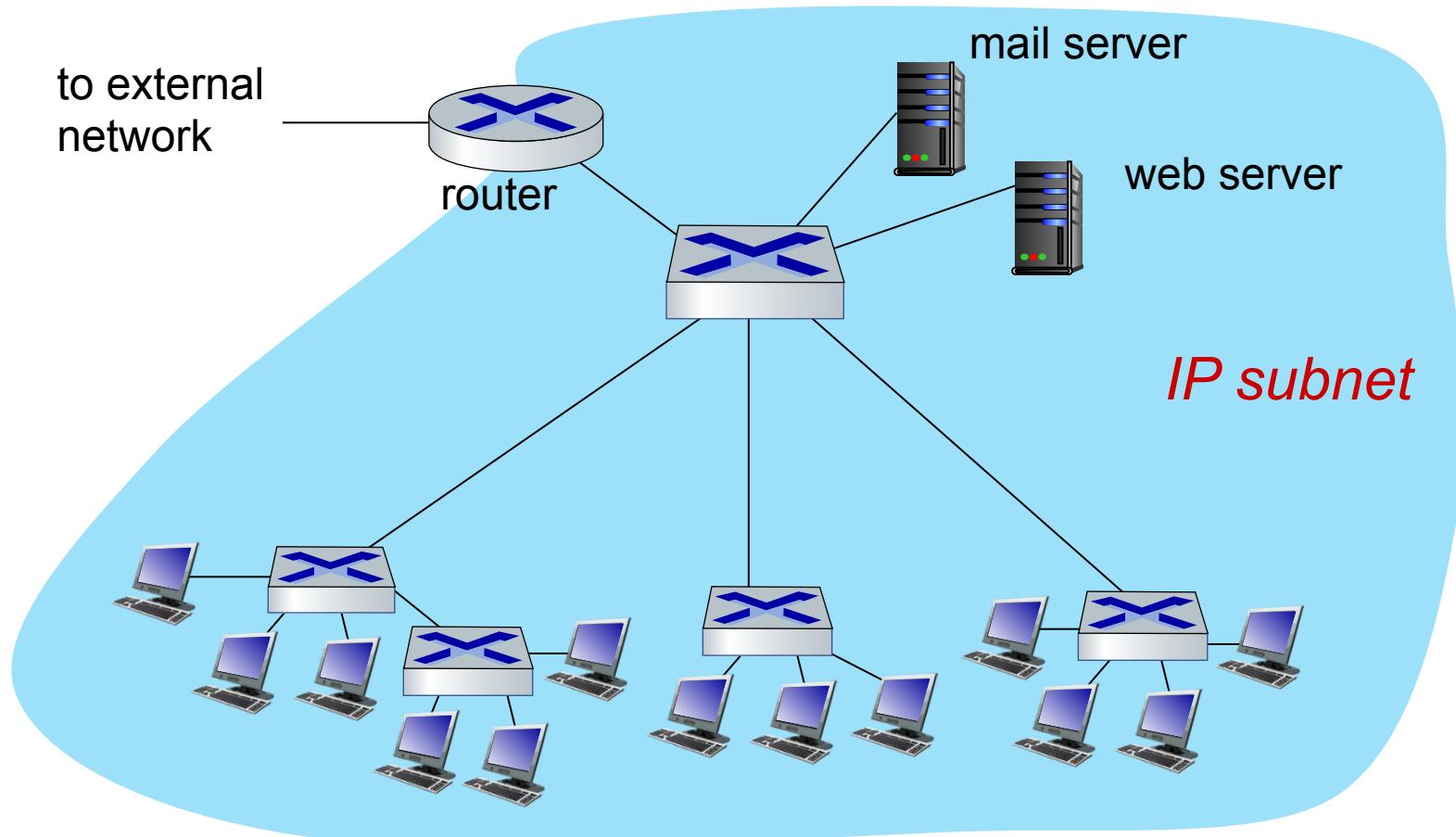
Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



Q: show switch tables and packet forwarding in S_1, S_2, S_3, S_4

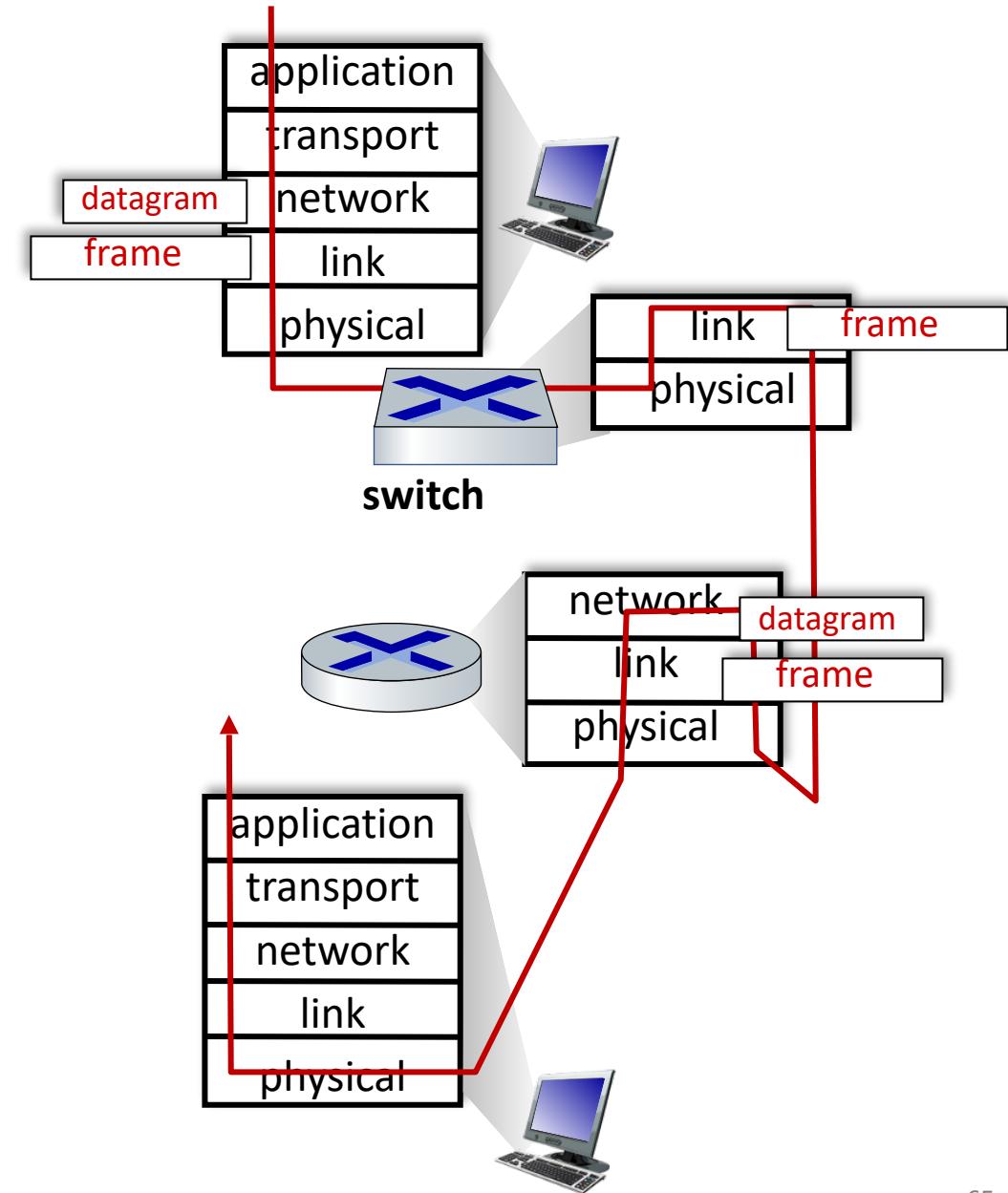
Small institutional network



Switches vs. routers

both are store-and-forward:

- *routers*: network-layer devices (examine network-layer headers)
- *switches*: link-layer devices (examine link-layer headers)



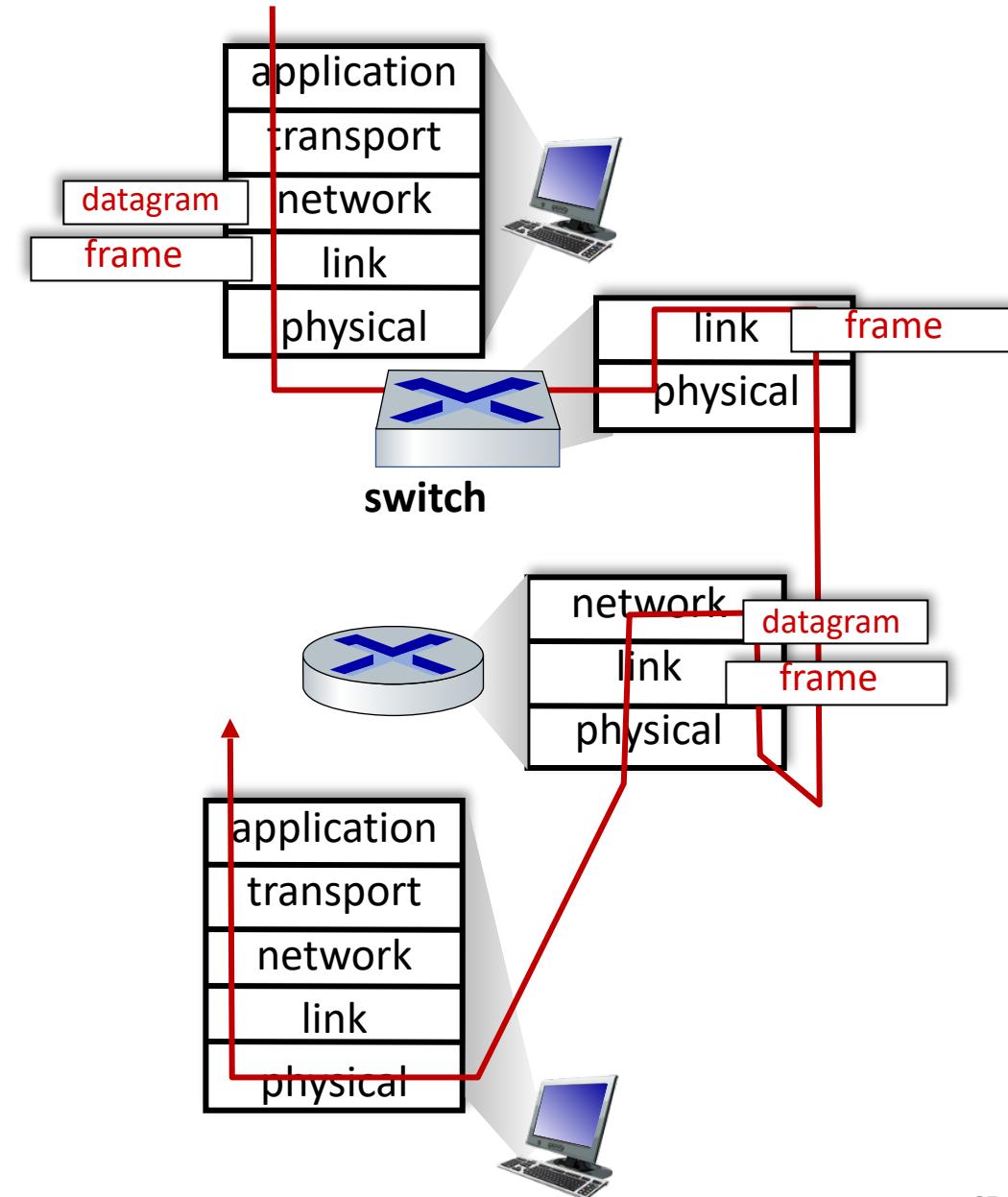
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both have forwarding tables:

- *routers*: compute tables using routing algorithms, IP addresses
- *switches*: learn forwarding table using flooding, learning, MAC addresses



Chapter 5: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
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- **datacenter networking**
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Datacenter networks

10's to 100's of thousands of hosts, often closely coupled, in close proximity:

- e-business (e.g. Amazon)
- content-servers (e.g., YouTube, Akamai, Apple, Microsoft)
- search engines, data mining (e.g., Google)



Inside a 40-ft Microsoft container, Chicago data center

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challenges:

- multiple applications, each serving massive numbers of clients
- reliability
- managing/balancing load, avoiding processing, networking, data bottlenecks



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Datacenter networks: network elements

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Server racks

- 20- 40 server blades: hosts

Datacenter networks: network elements



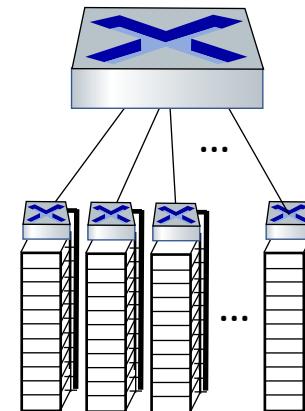
Top of Rack (TOR) switch

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Tier-2 switches

- connecting to ~16 TORs below

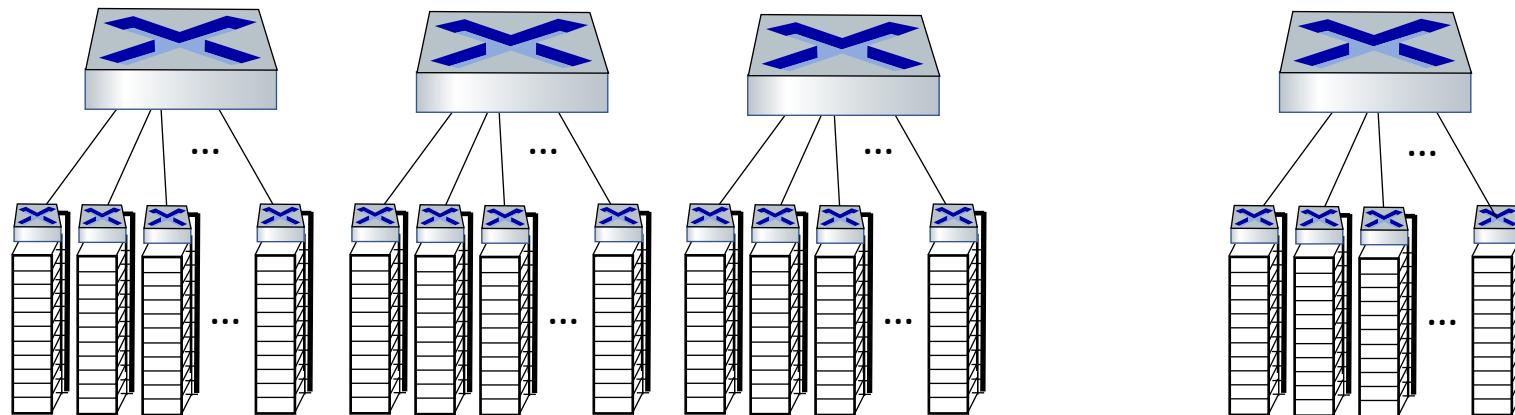
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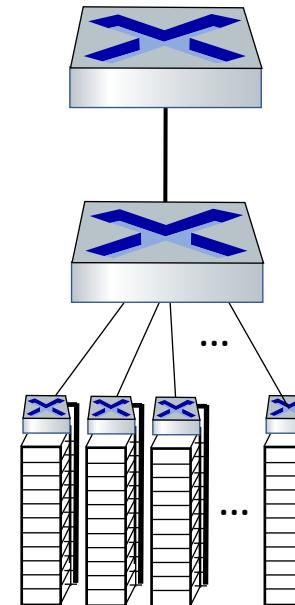
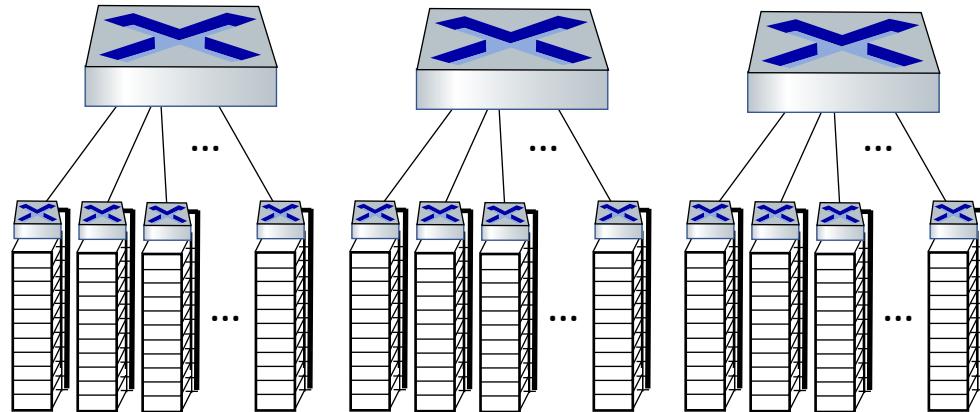
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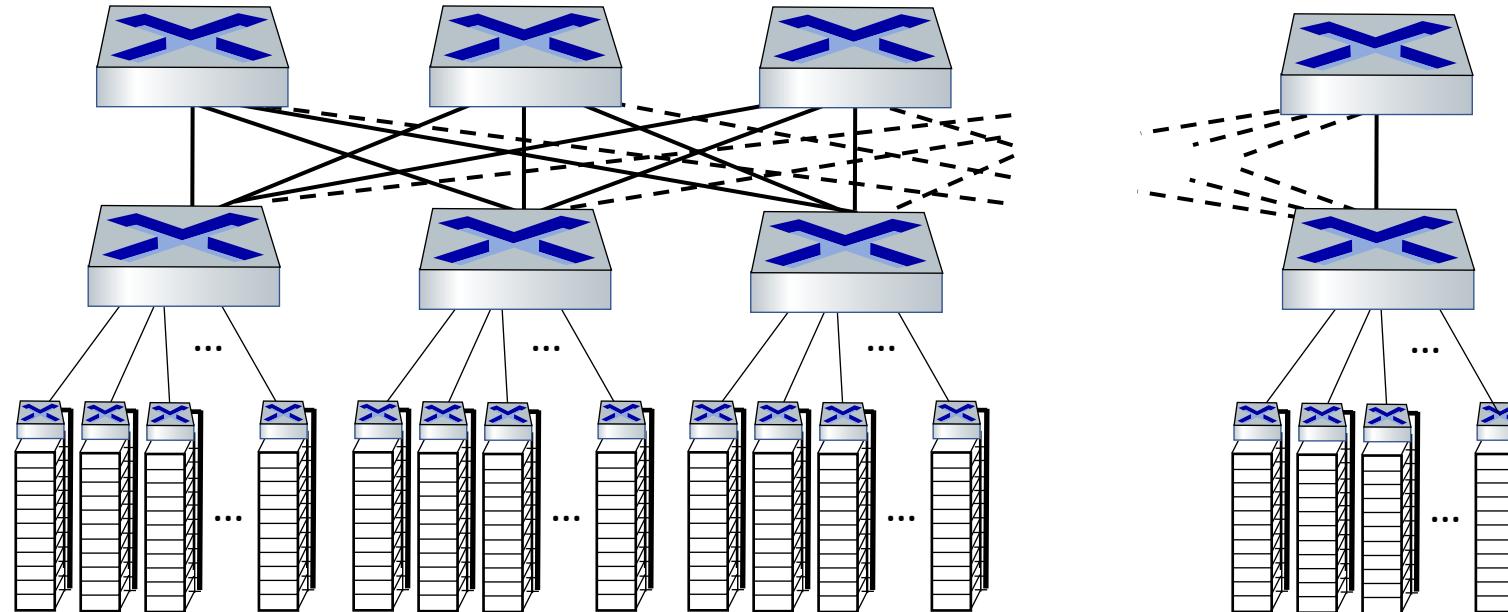
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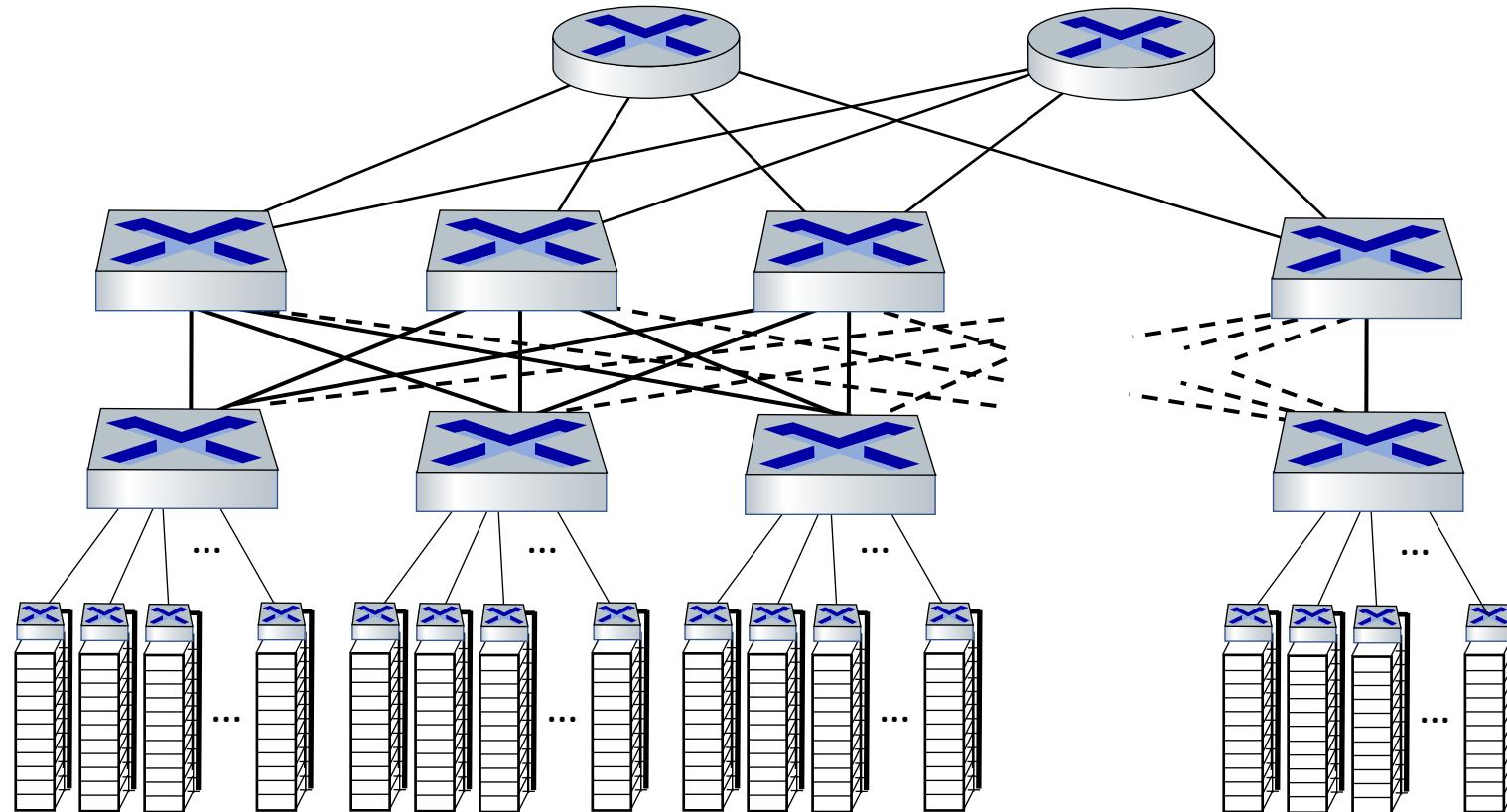
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Border routers

- connections outside datacenter

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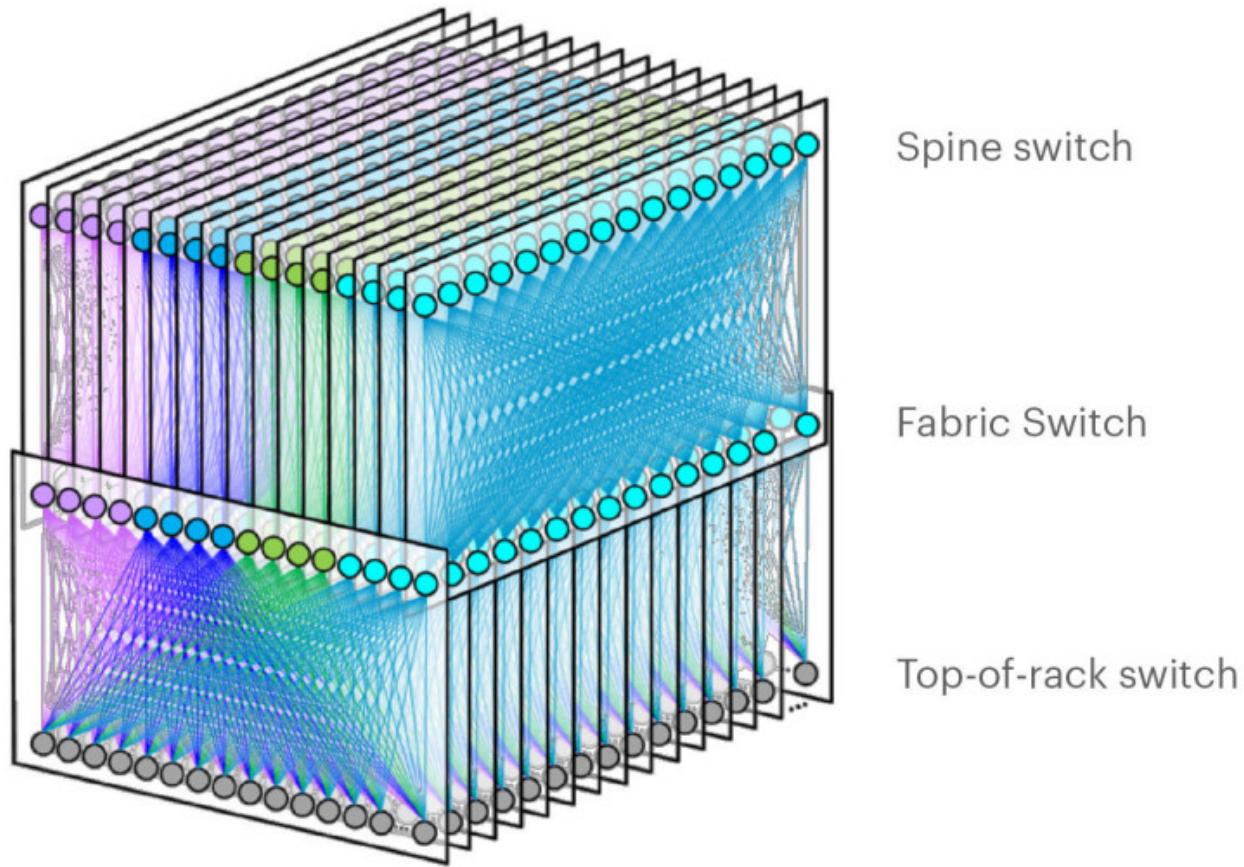
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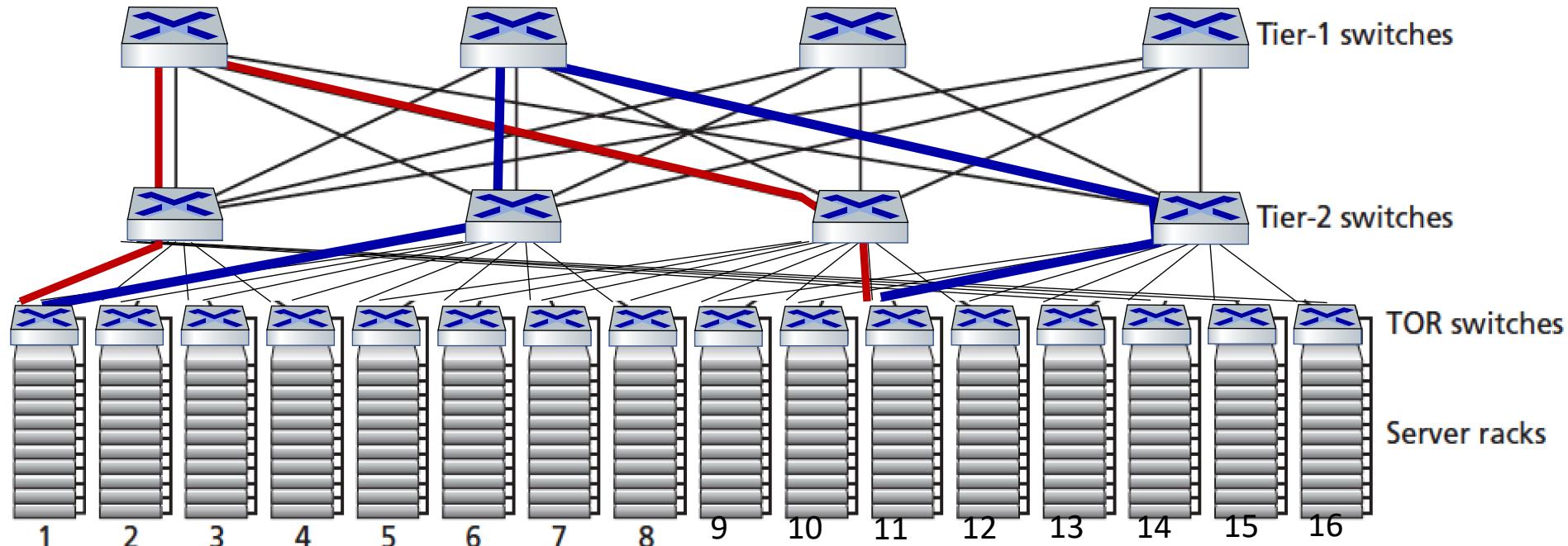
Facebook F16 data center network topology:



<https://engineering.fb.com/data-center-engineering/f16-minipack/> (posted 3/2019)

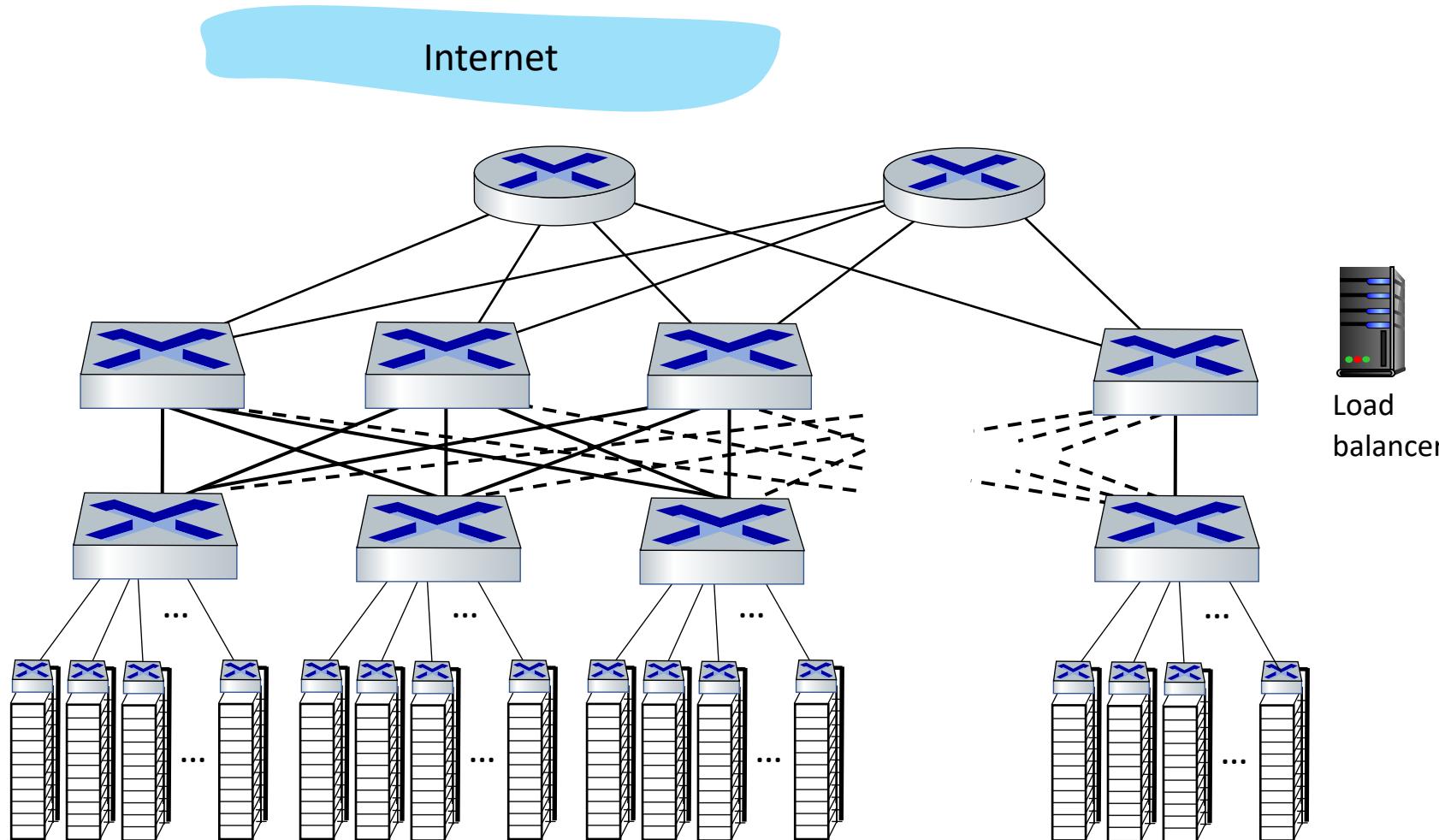
Datacenter networks: multipath

- rich interconnection among switches, racks:
 - increased throughput between racks (multiple routing paths possible)
 - increased reliability via redundancy



two **disjoint** paths highlighted between racks 1 and 11

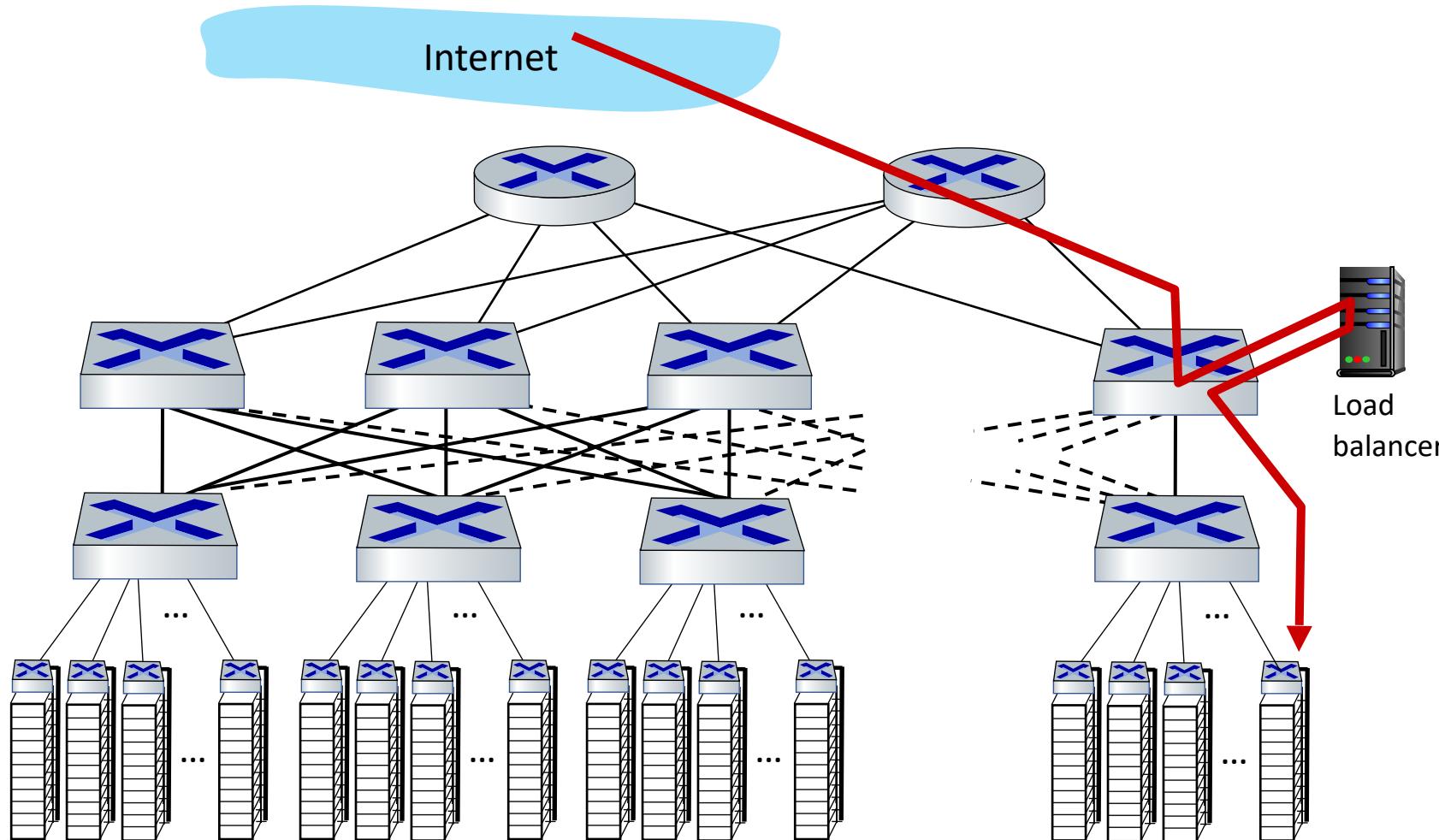
Datacenter networks: application-layer routing



**load balancer:
application-layer
routing**

- receives external client requests
- directs workload within data center

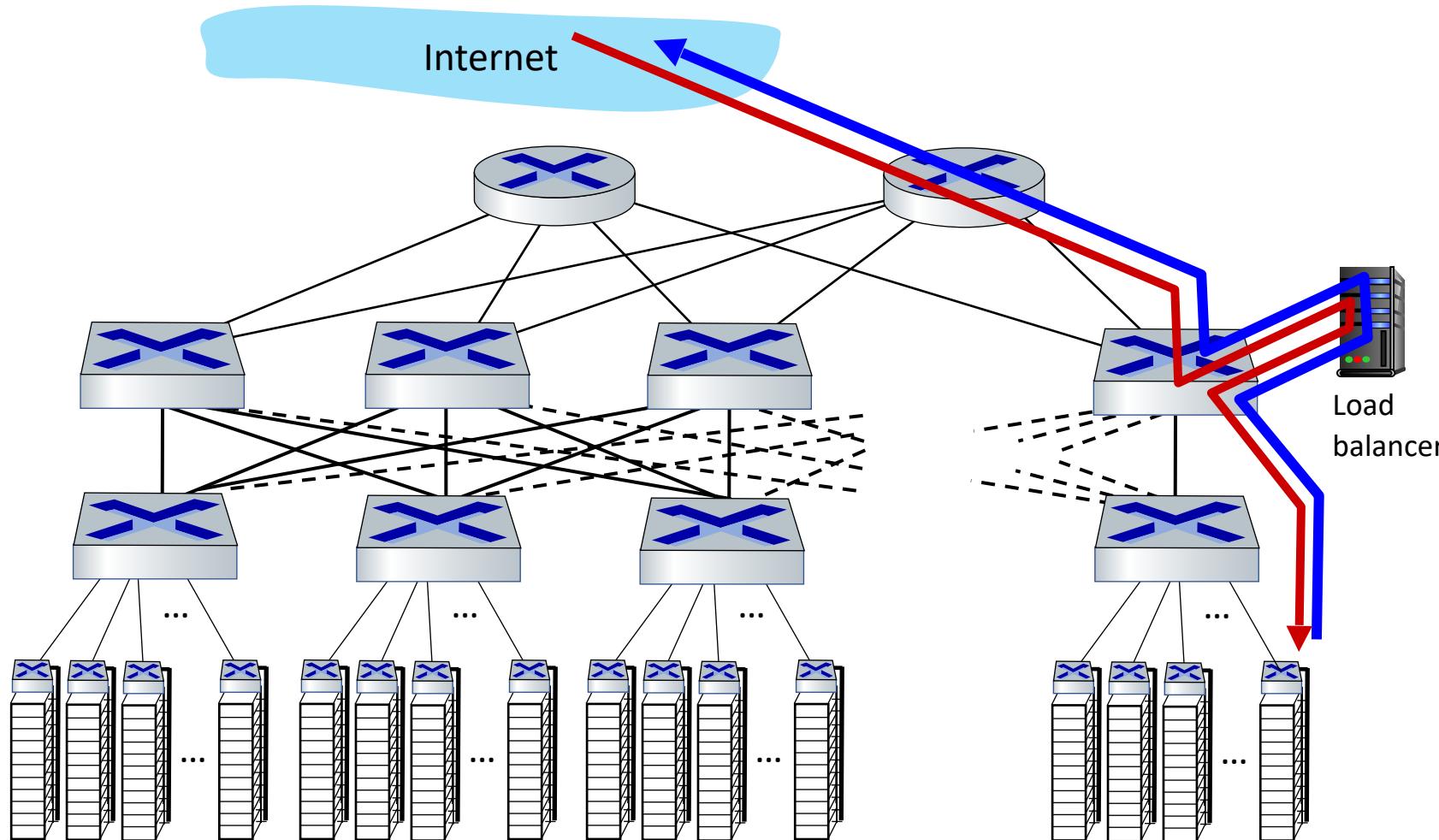
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Datacenter networks: application-layer routing



load balancer:
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- directs workload within data center
- returns results to external client (hiding data center internals from client)

Datacenter networks: protocol innovations

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 - ECN (explicit congestion notification) used in transport-layer congestion control (DCTCP, DCQCN)
 - experimentation with hop-by-hop (backpressure) congestion control

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- transport layer:
 - ECN (explicit congestion notification) used in transport-layer congestion control (DCTCP, DCQCN)
 - experimentation with hop-by-hop (backpressure) congestion control
- routing, management:
 - SDN widely used within/among organizations' datacenters
 - place related services, data as close as possible (e.g., in same rack or nearby rack) to minimize tier-2, tier-1 communication

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Synthesis: a day in the life of a web request

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Synthesis: a day in the life of a web request

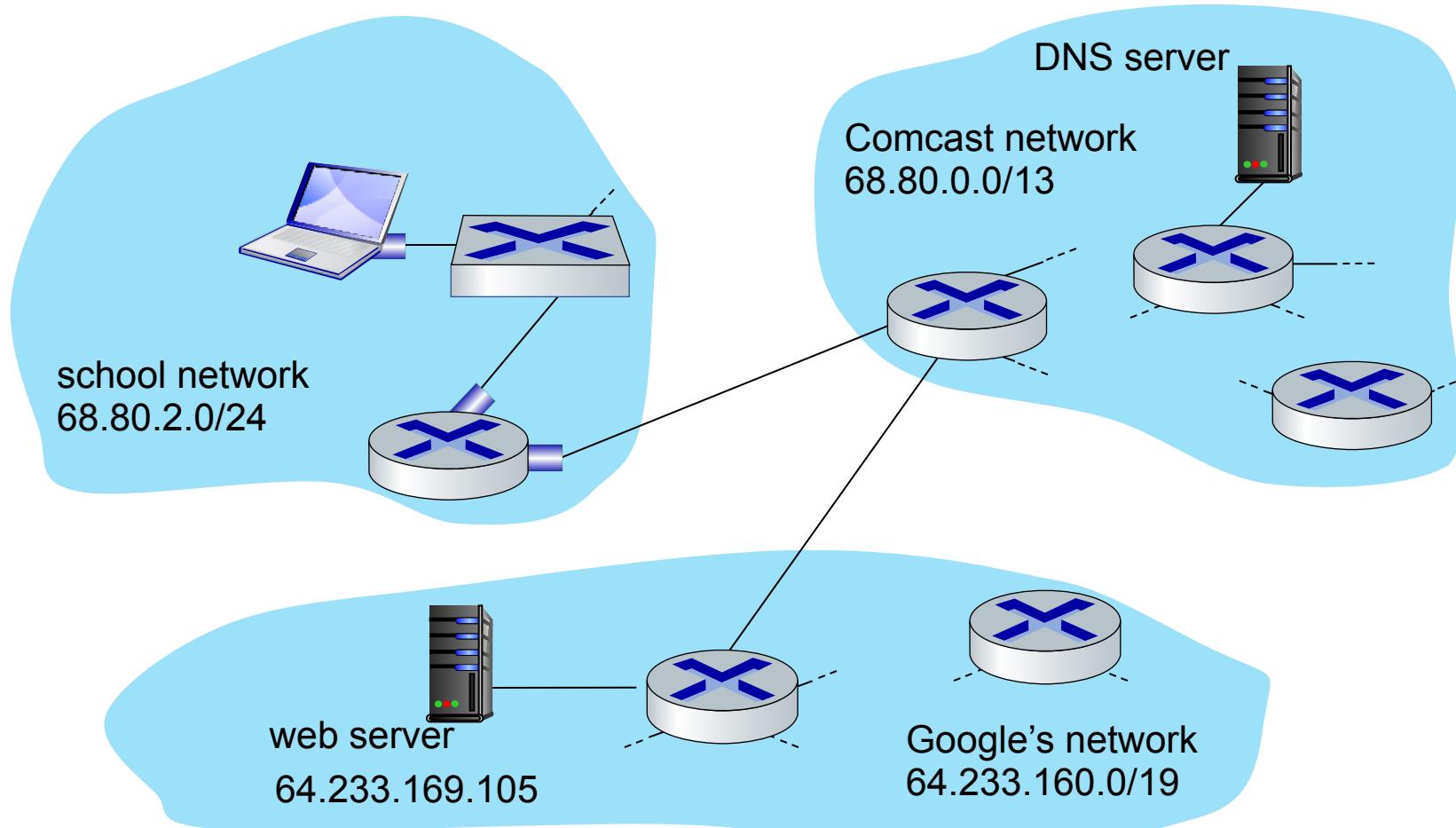
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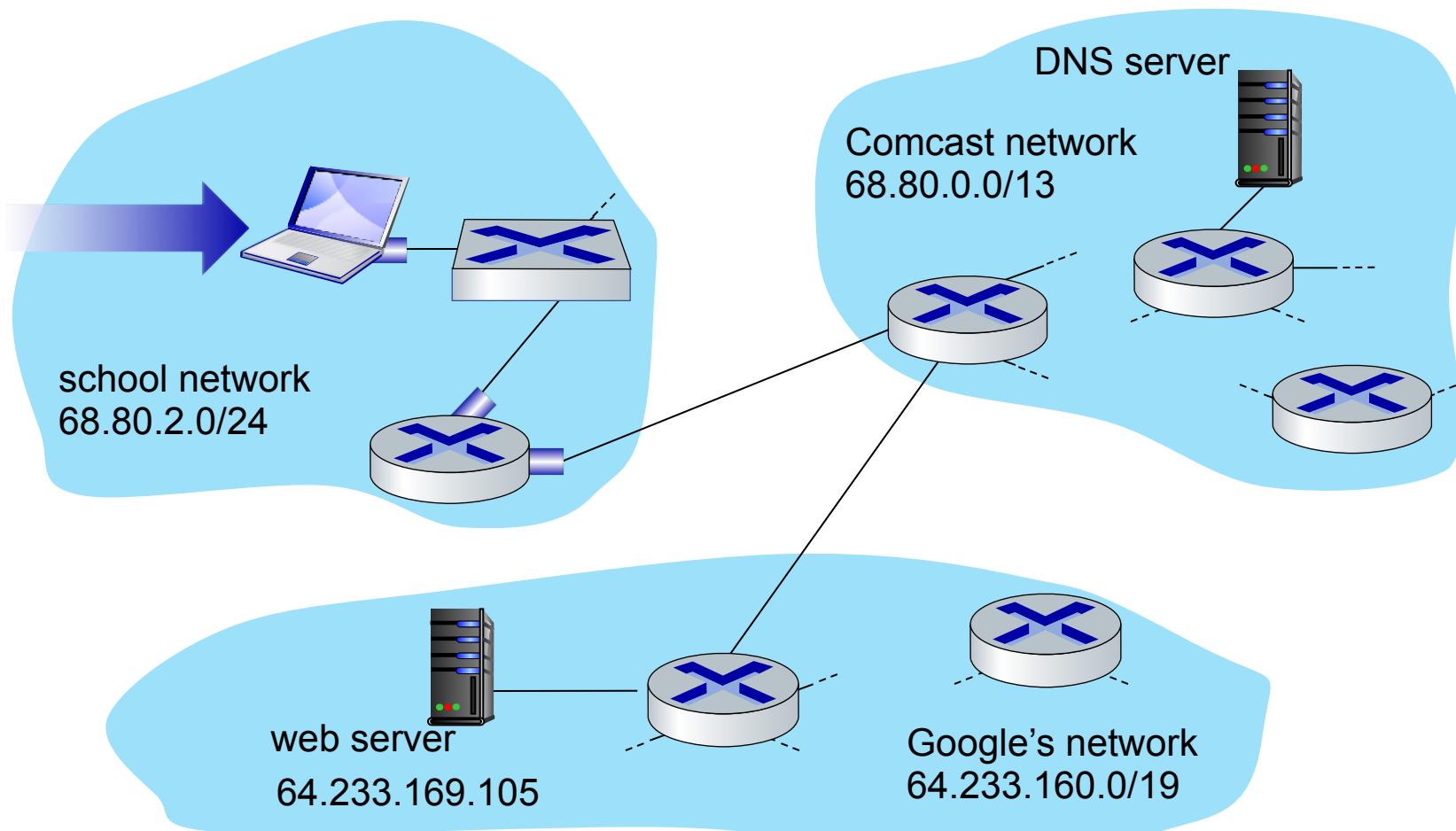
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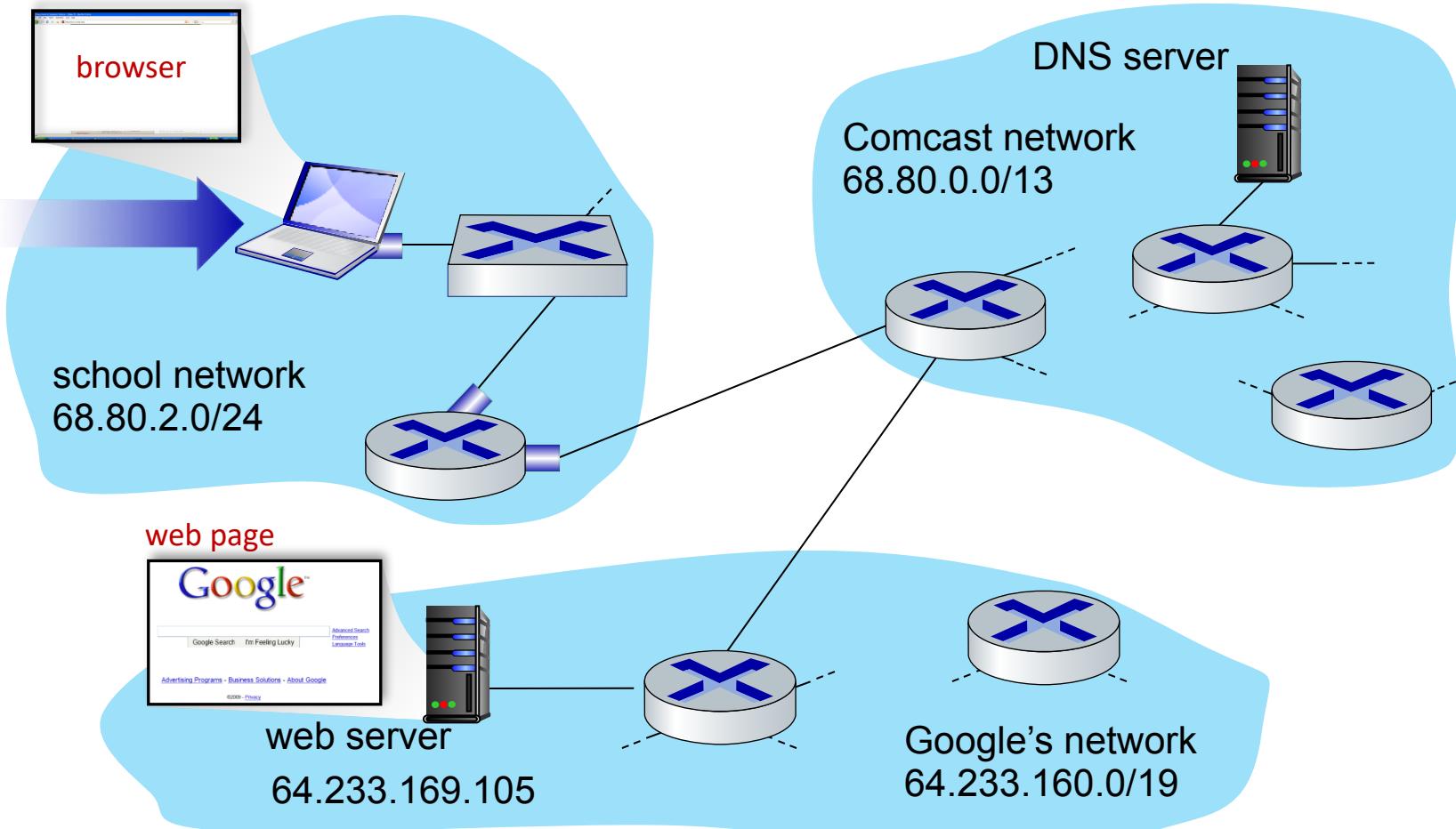
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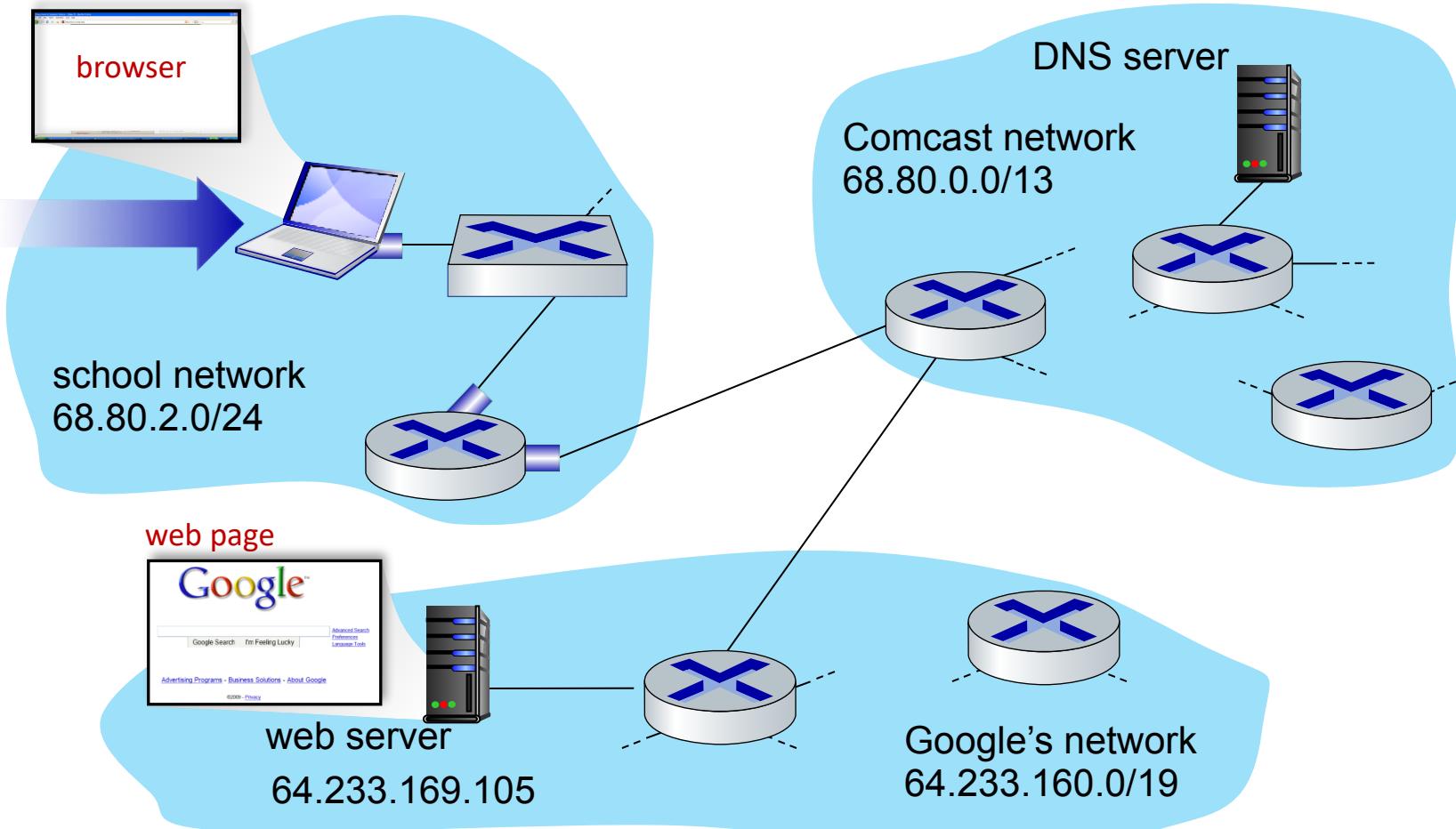
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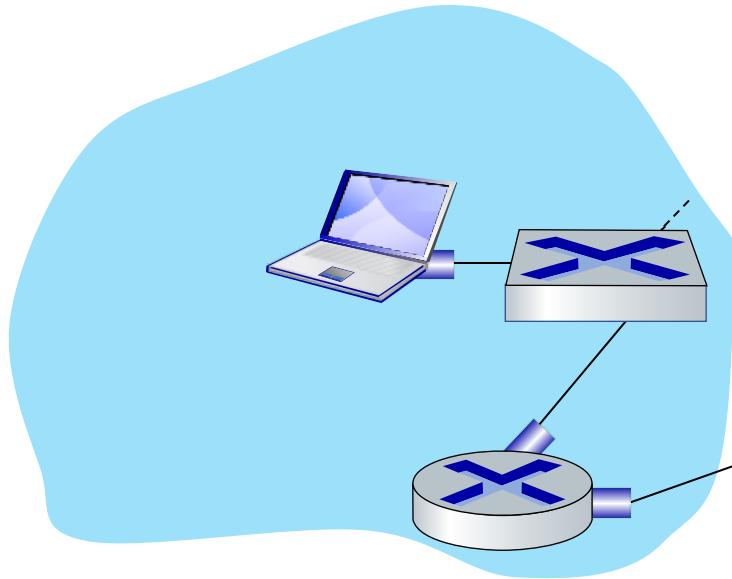


scenario:

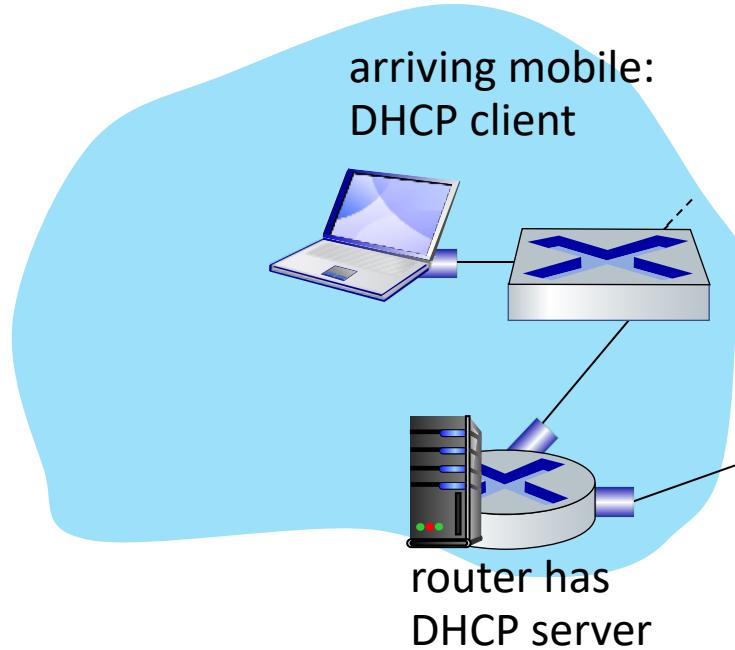
- arriving mobile client attaches to network ...
- requests web page:
www.google.com

Sounds simple! !

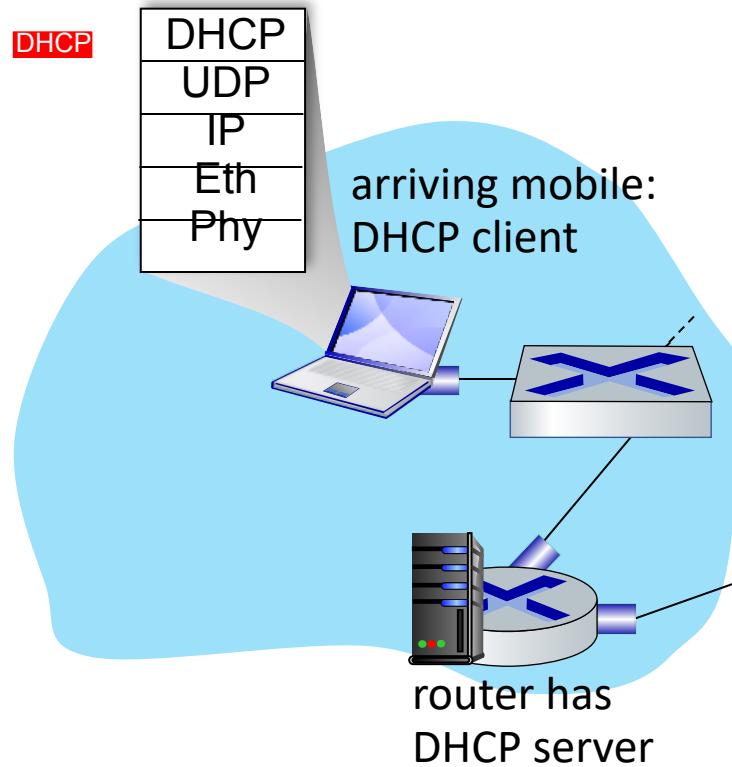
A day in the life: connecting to the Internet



A day in the life: connecting to the Internet

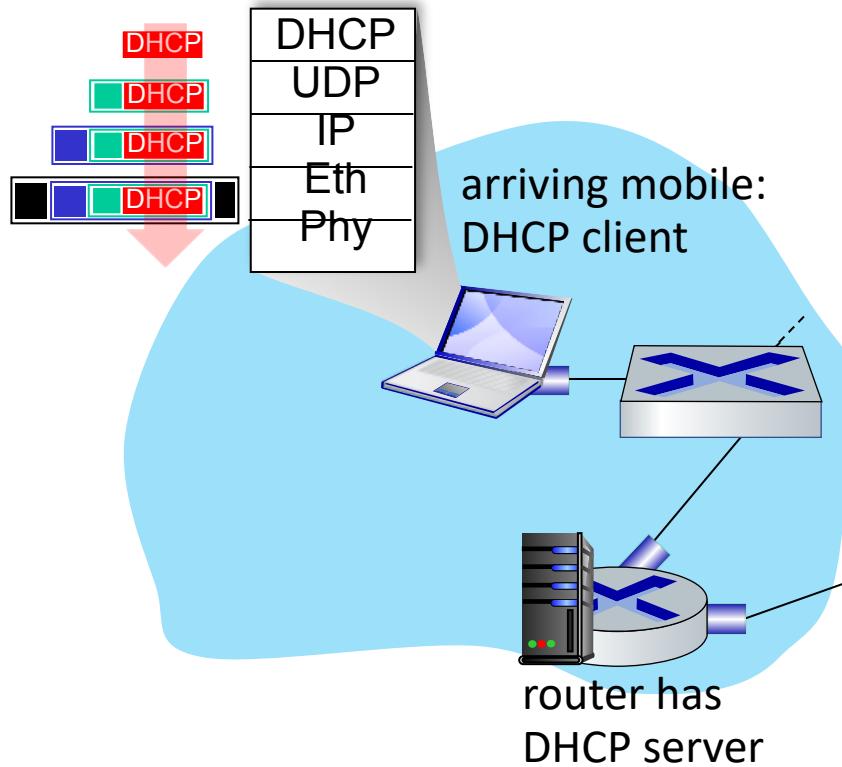


A day in the life: connecting to the Internet



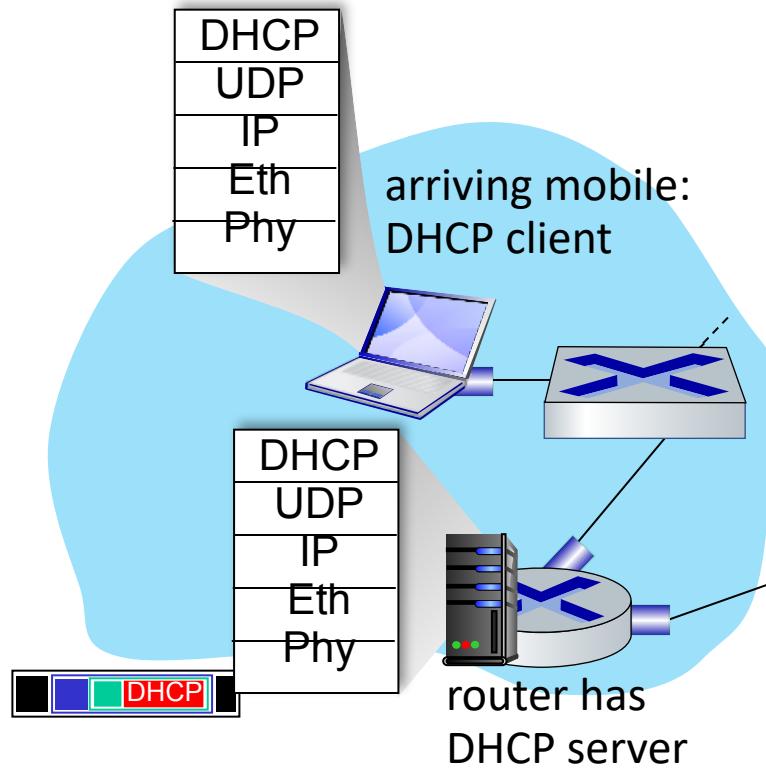
- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use **DHCP**

A day in the life: connecting to the Internet



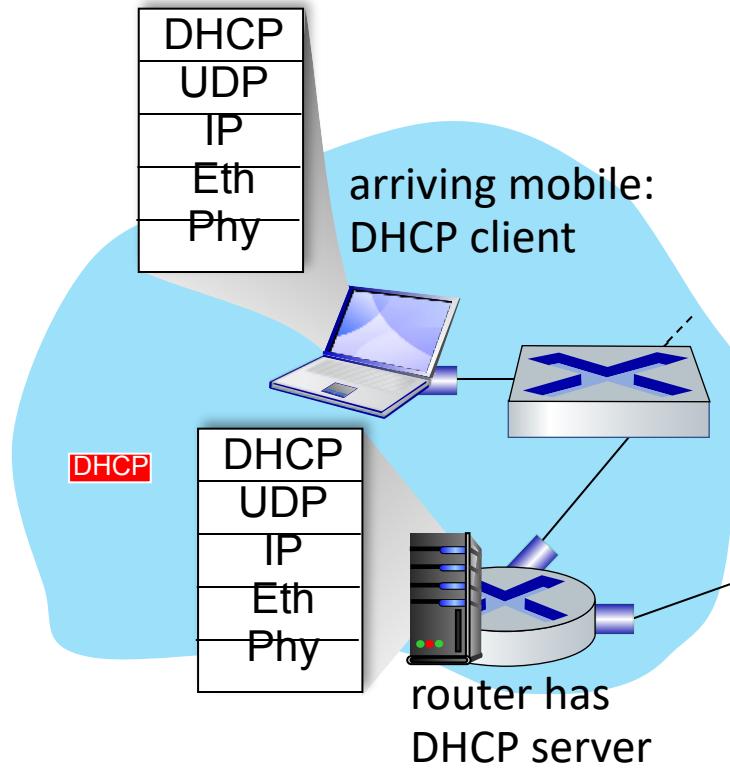
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A day in the life: connecting to the Internet



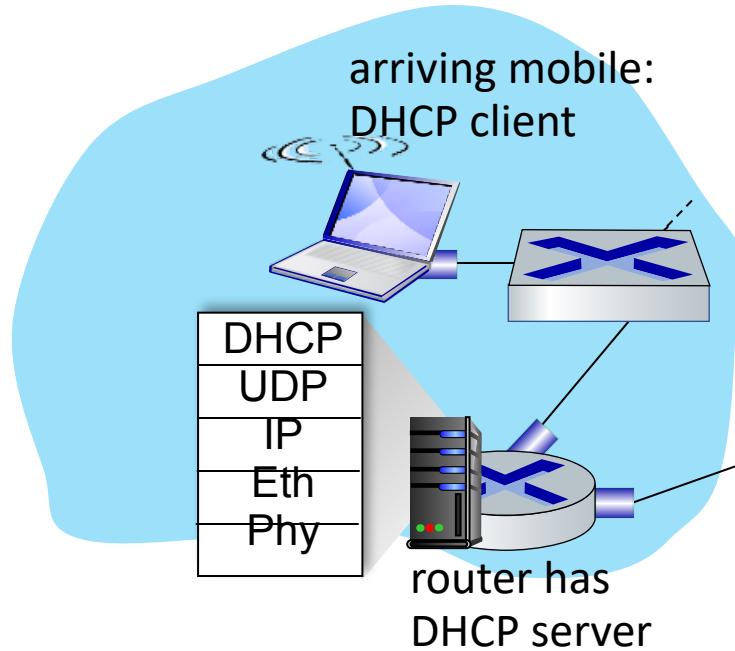
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- Ethernet frame **broadcast** (dest: FFFFFFFFFFFF) on LAN, received at router running **DHCP server**

A day in the life: connecting to the Internet

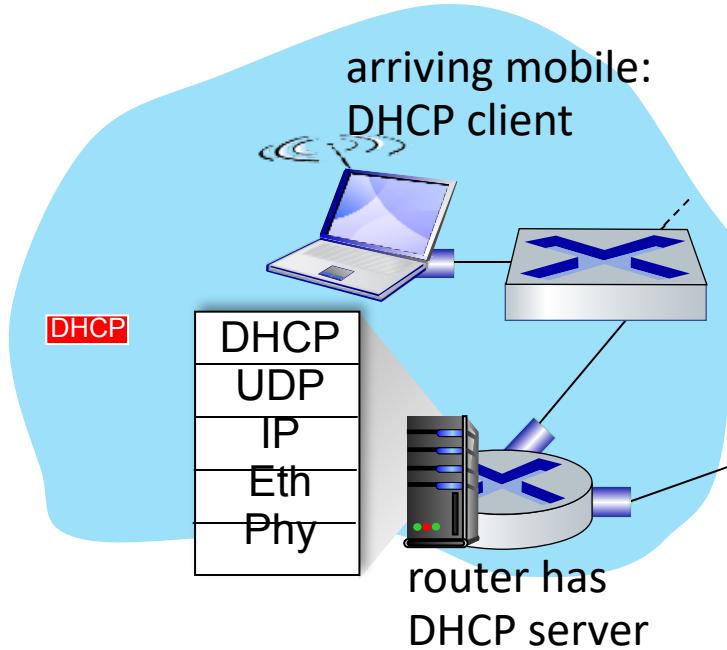


- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use **DHCP**
- DHCP request encapsulated in **UDP**, encapsulated in **IP**, encapsulated in **802.3** Ethernet
- Ethernet frame **broadcast** (dest: FFFFFFFFFFFF) on LAN, received at router running **DHCP** server
- Ethernet **demuxed** to IP demuxed, UDP demuxed to DHCP

A day in the life: connecting to the Internet

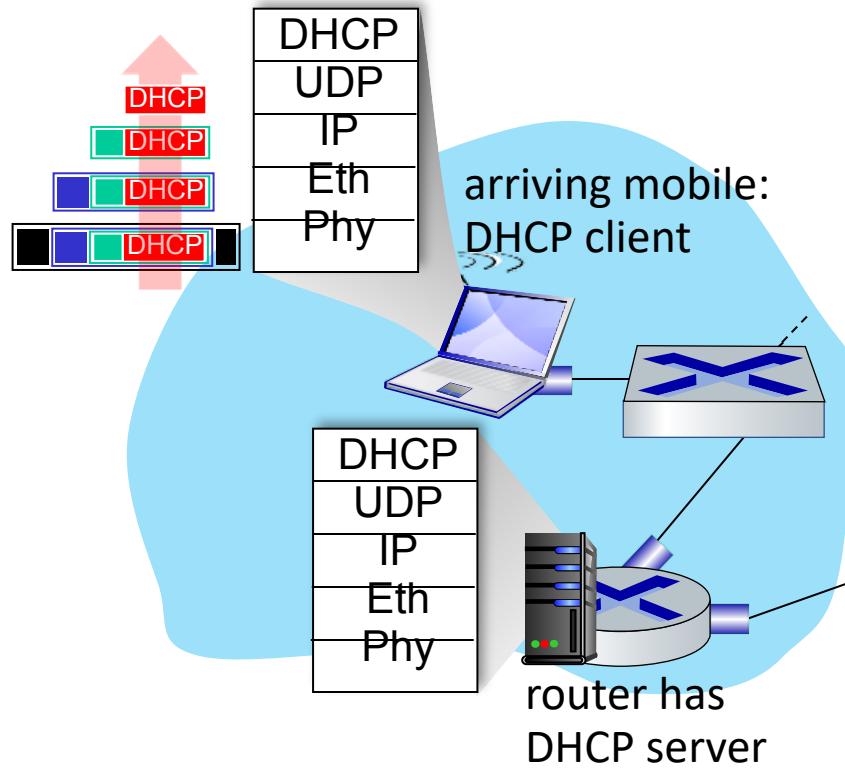


A day in the life: connecting to the Internet



- DHCP server formulates **DHCP ACK** containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server

A day in the life: connecting to the Internet

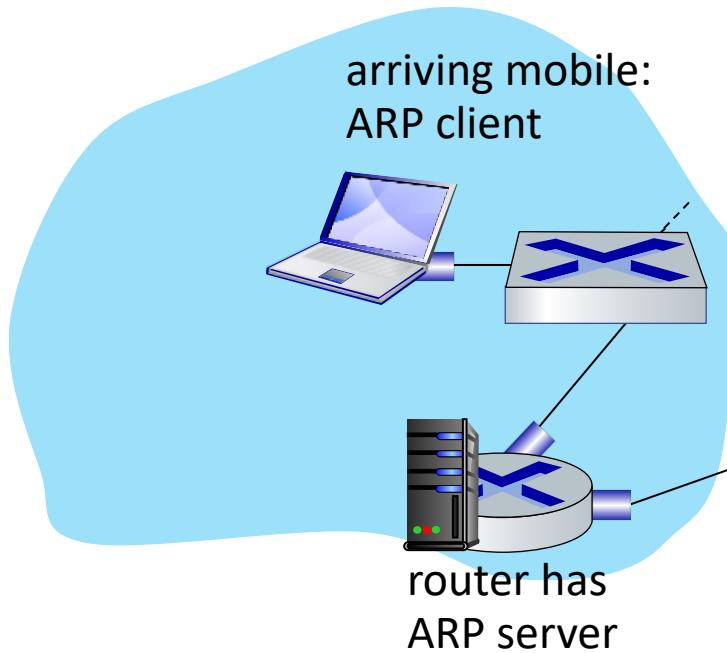


- DHCP server formulates **DHCP ACK** containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation at DHCP server, frame forwarded (**switch learning**) through LAN, demultiplexing at client
- DHCP client receives DHCP ACK reply

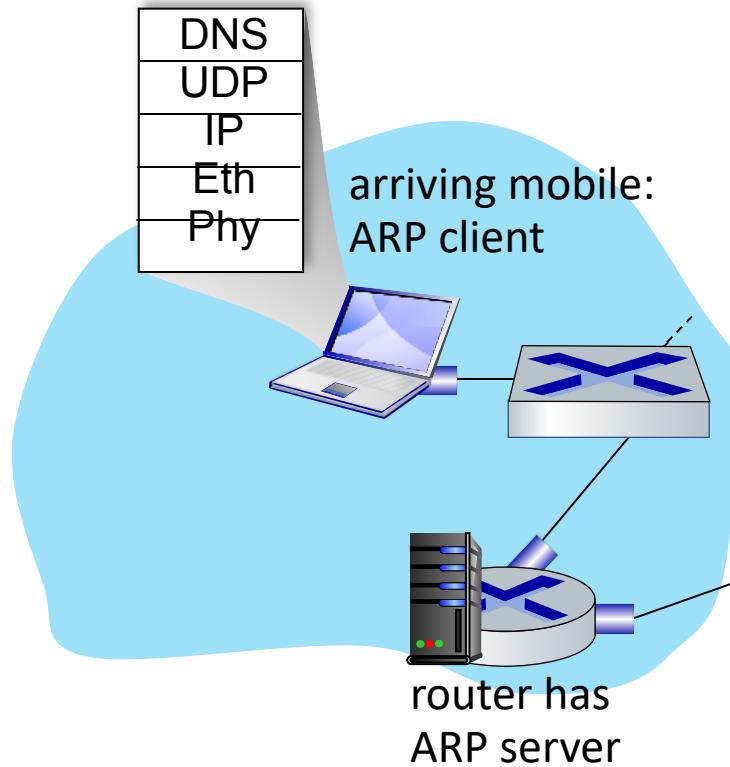
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

A day in the life... ARP (before DNS, before HTTP)

- before sending **HTTP** request, need IP address of www.google.com: **DNS**

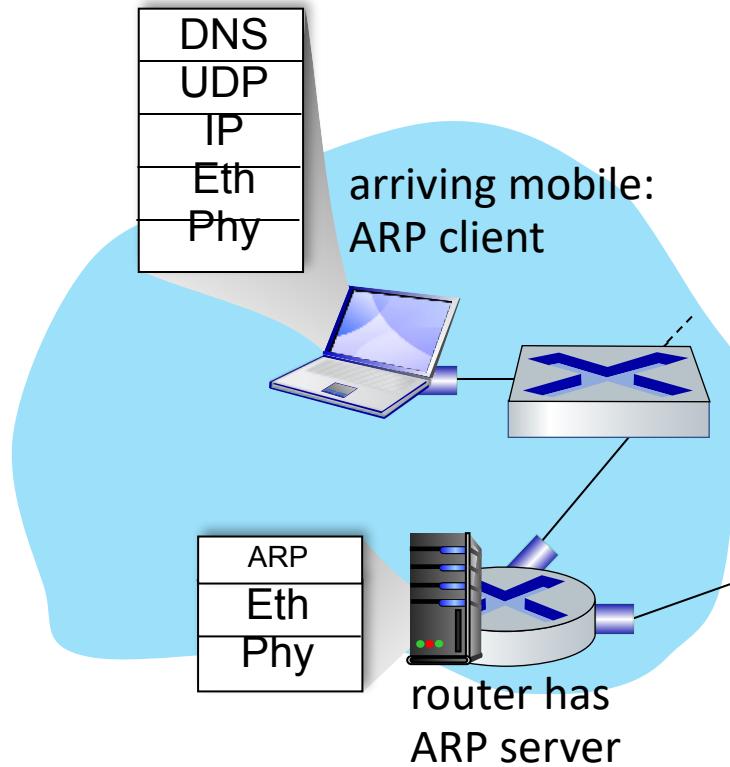


A day in the life... ARP (before DNS, before HTTP)



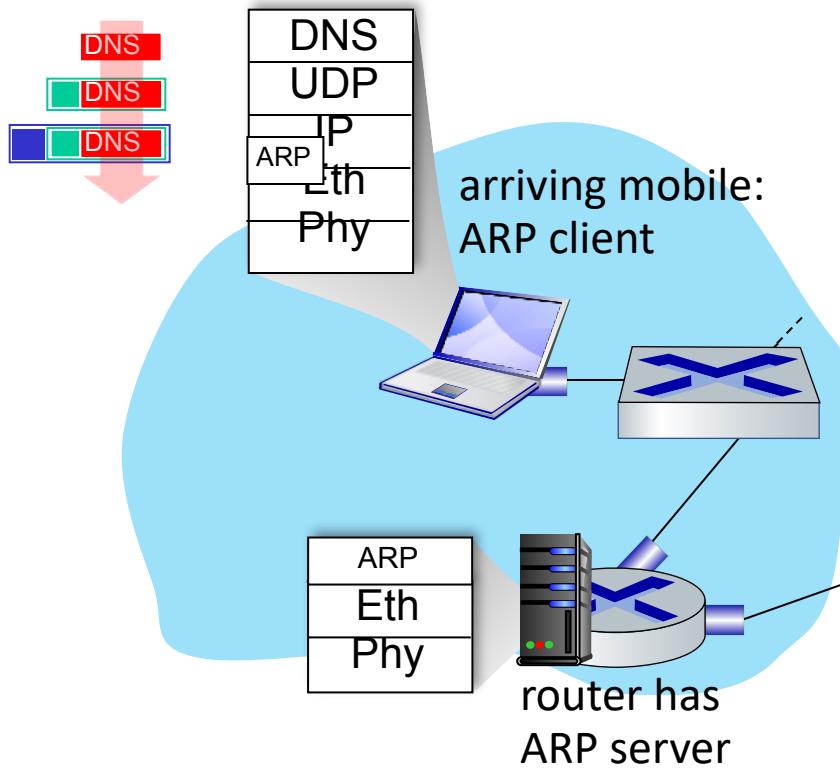
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A day in the life... ARP (before DNS, before HTTP)



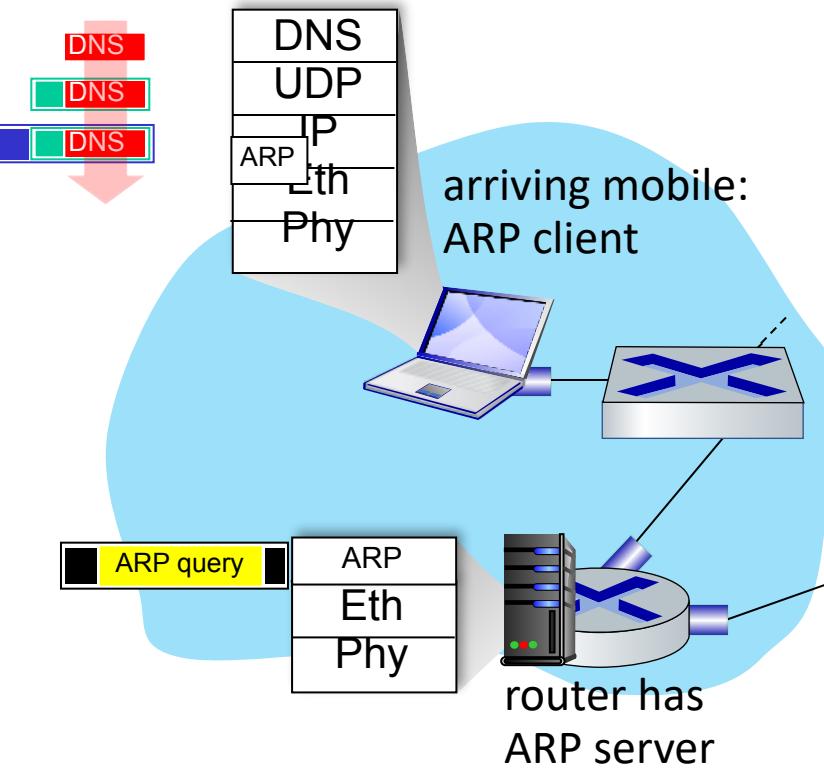
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A day in the life... ARP (before DNS, before HTTP)



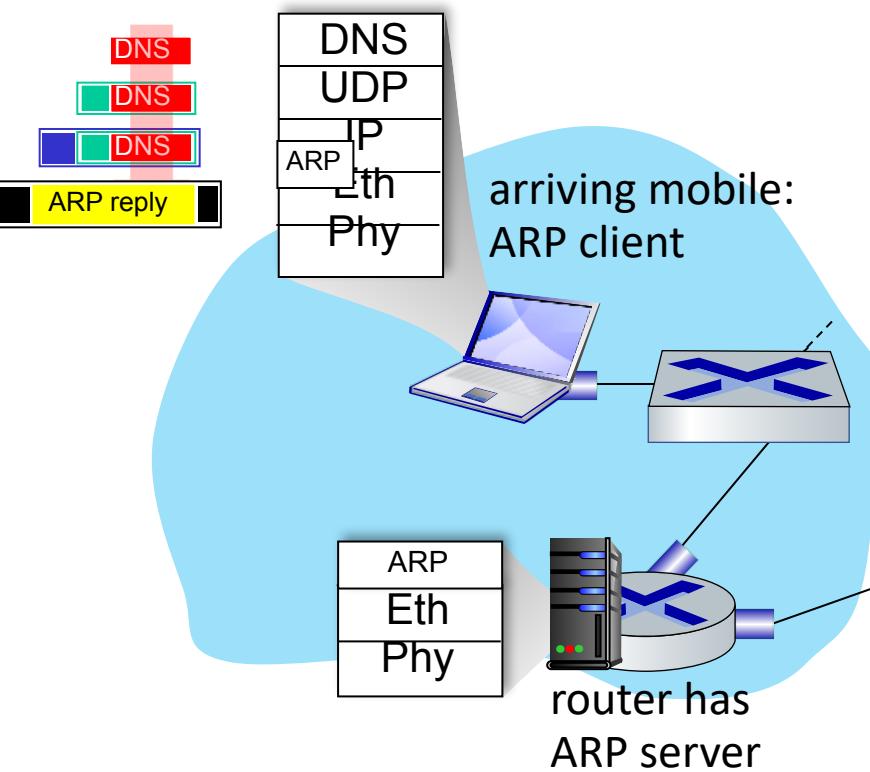
- before sending **HTTP** request, need IP address of www.google.com: **DNS**
- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: **ARP**

A day in the life... ARP (before DNS, before HTTP)



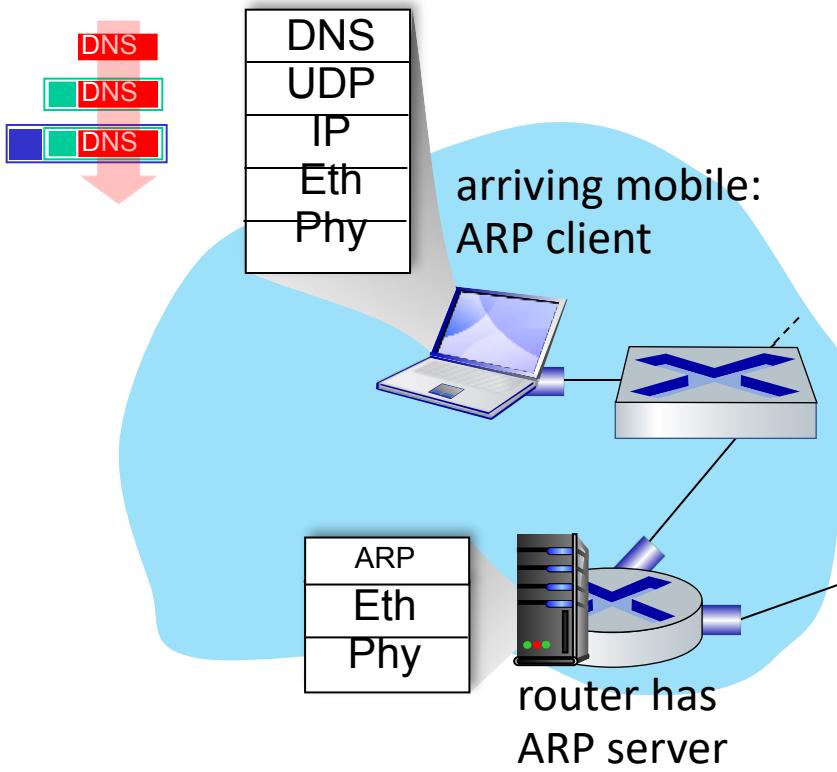
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A day in the life... ARP (before DNS, before HTTP)



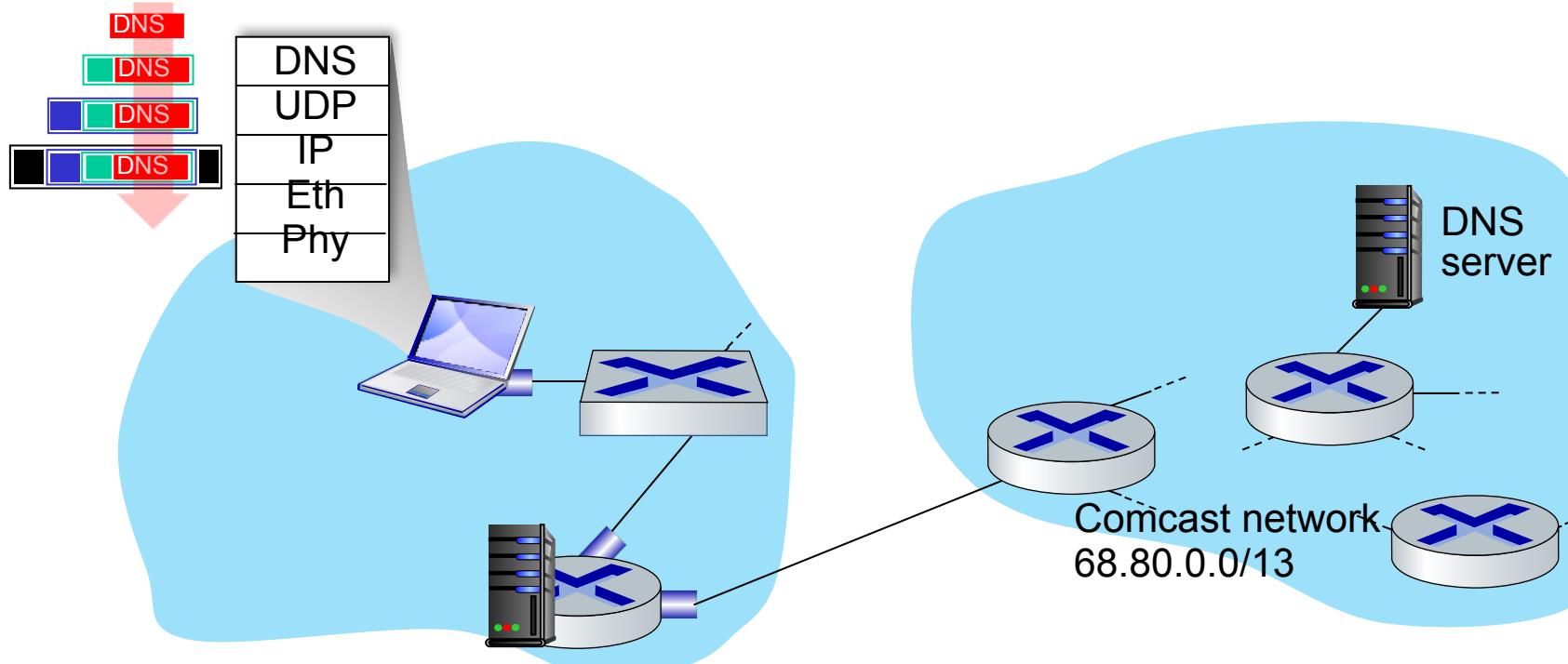
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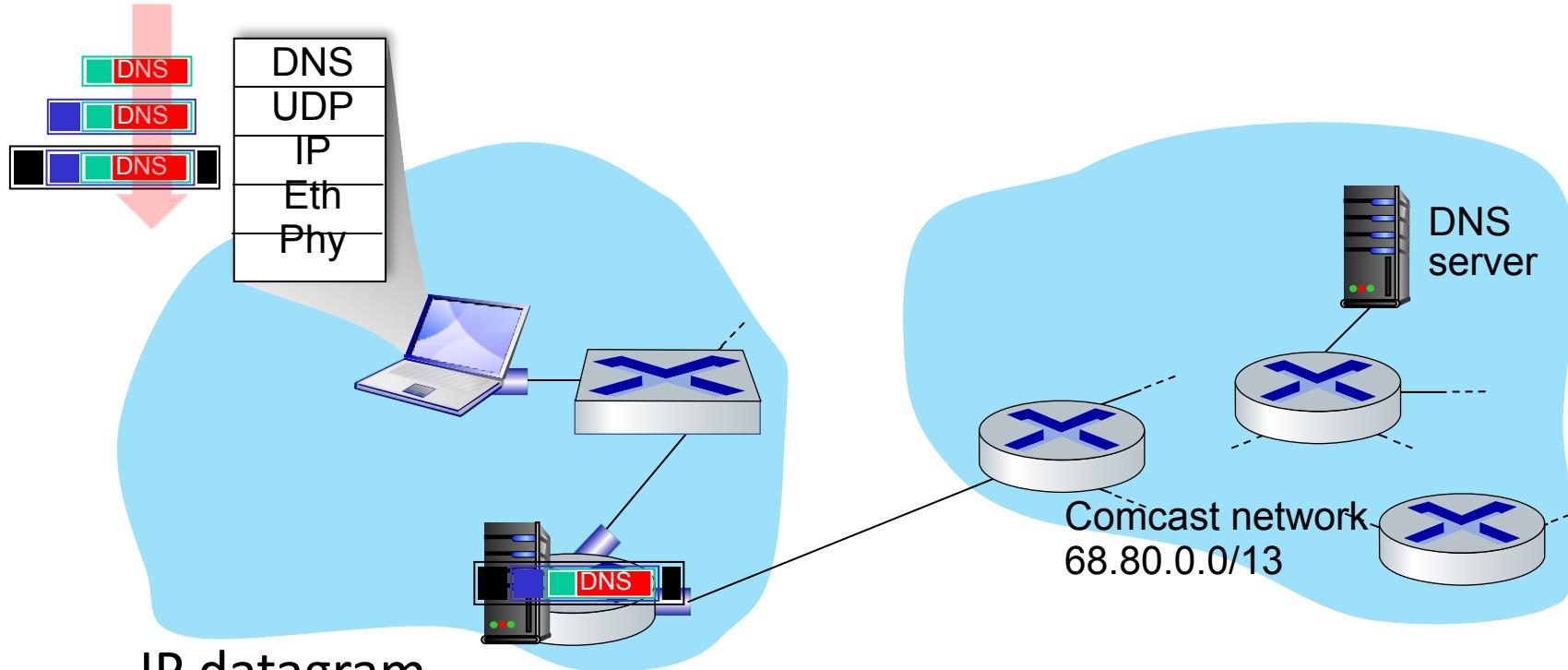


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- **ARP query** broadcast, received by router, which replies with **ARP reply** giving MAC address of router interface
- client now knows MAC address of first hop router, so can now send frame containing DNS query

A day in the life... using DNS

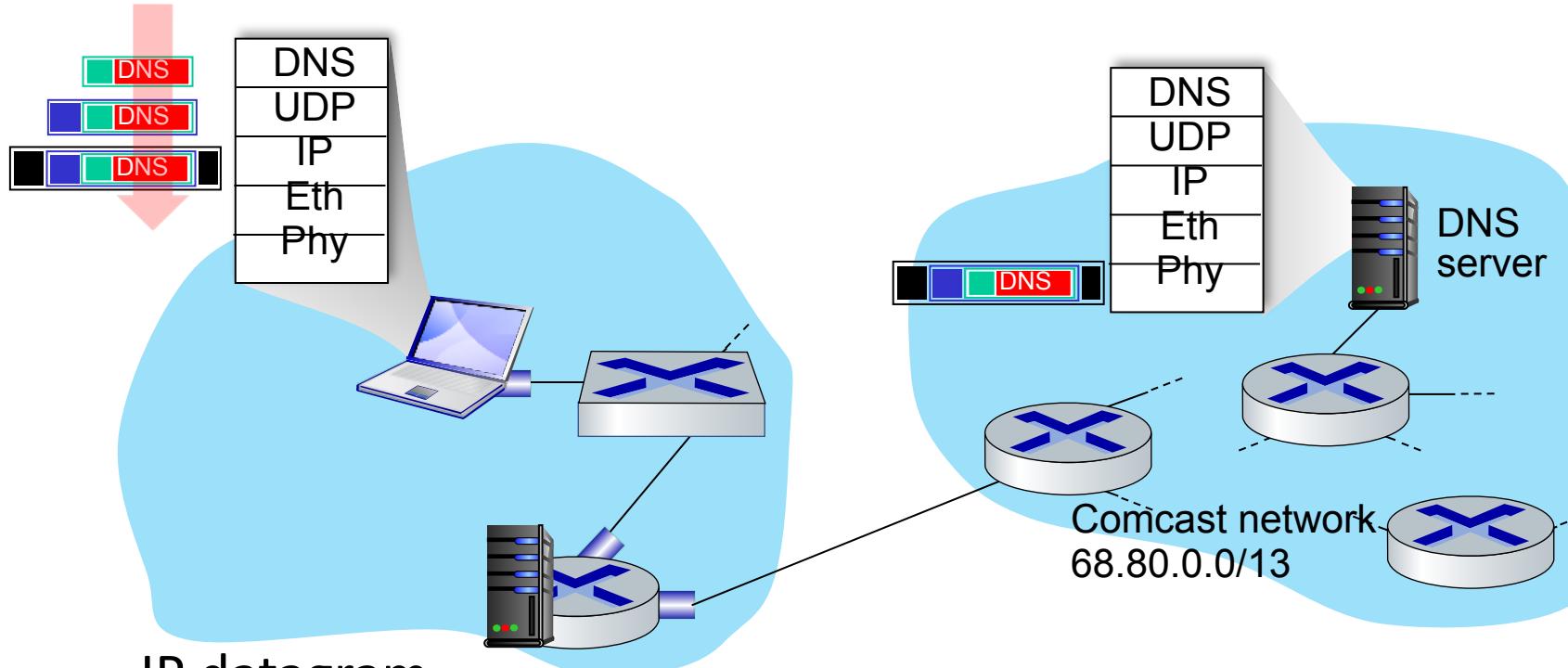


A day in the life... using DNS



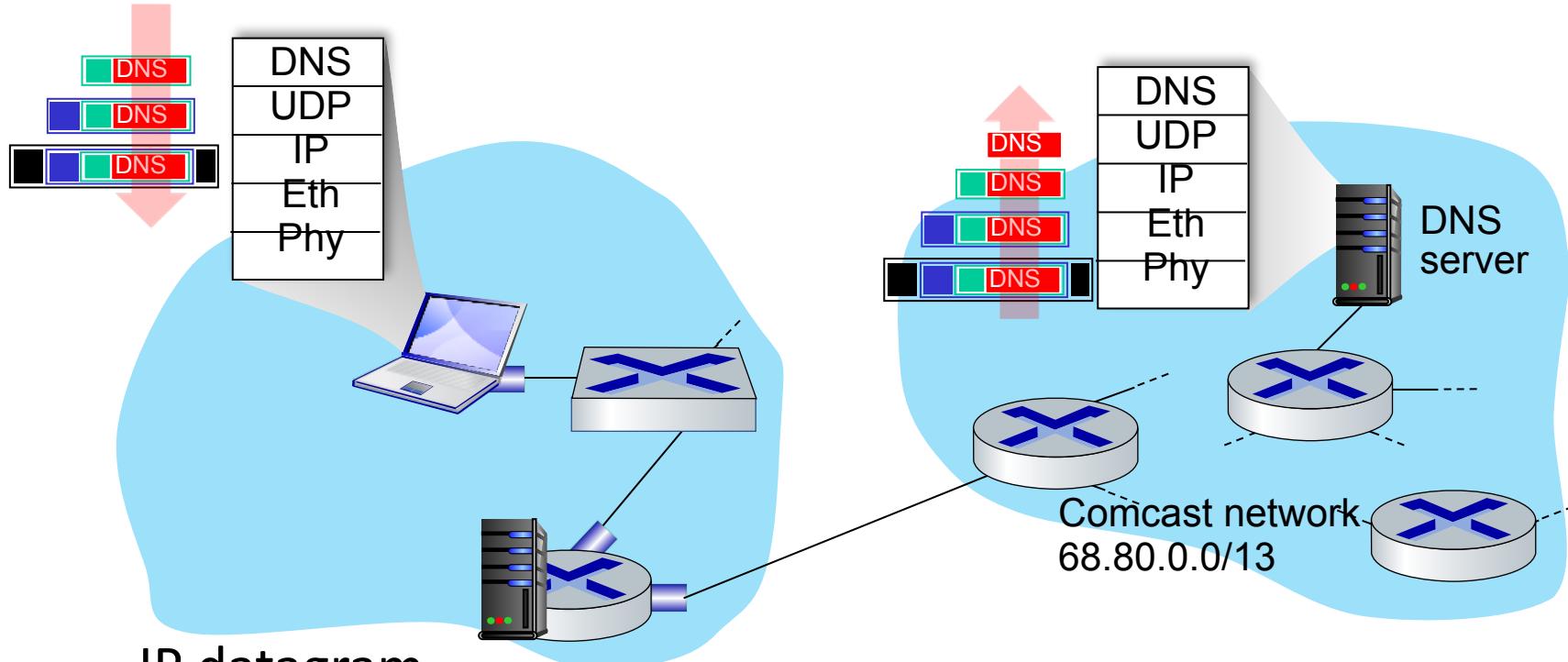
- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router

A day in the life... using DNS



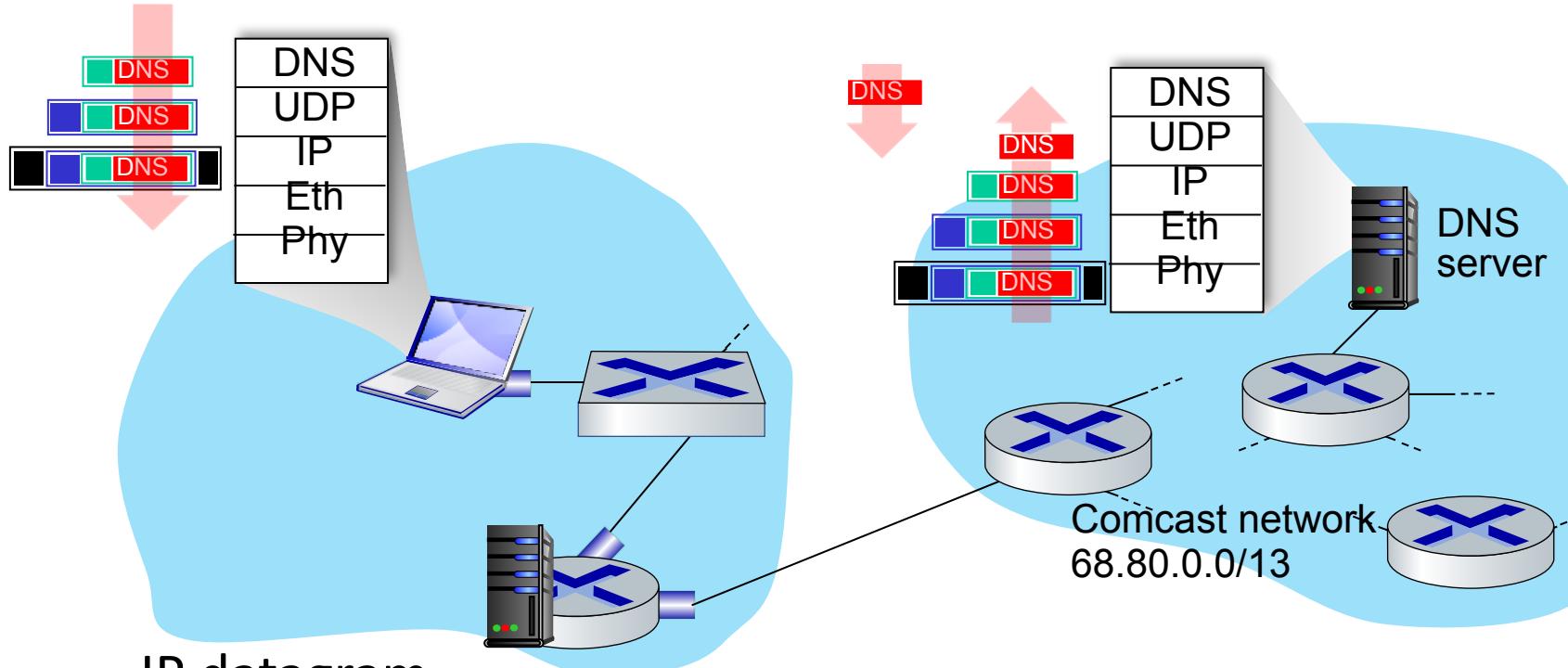
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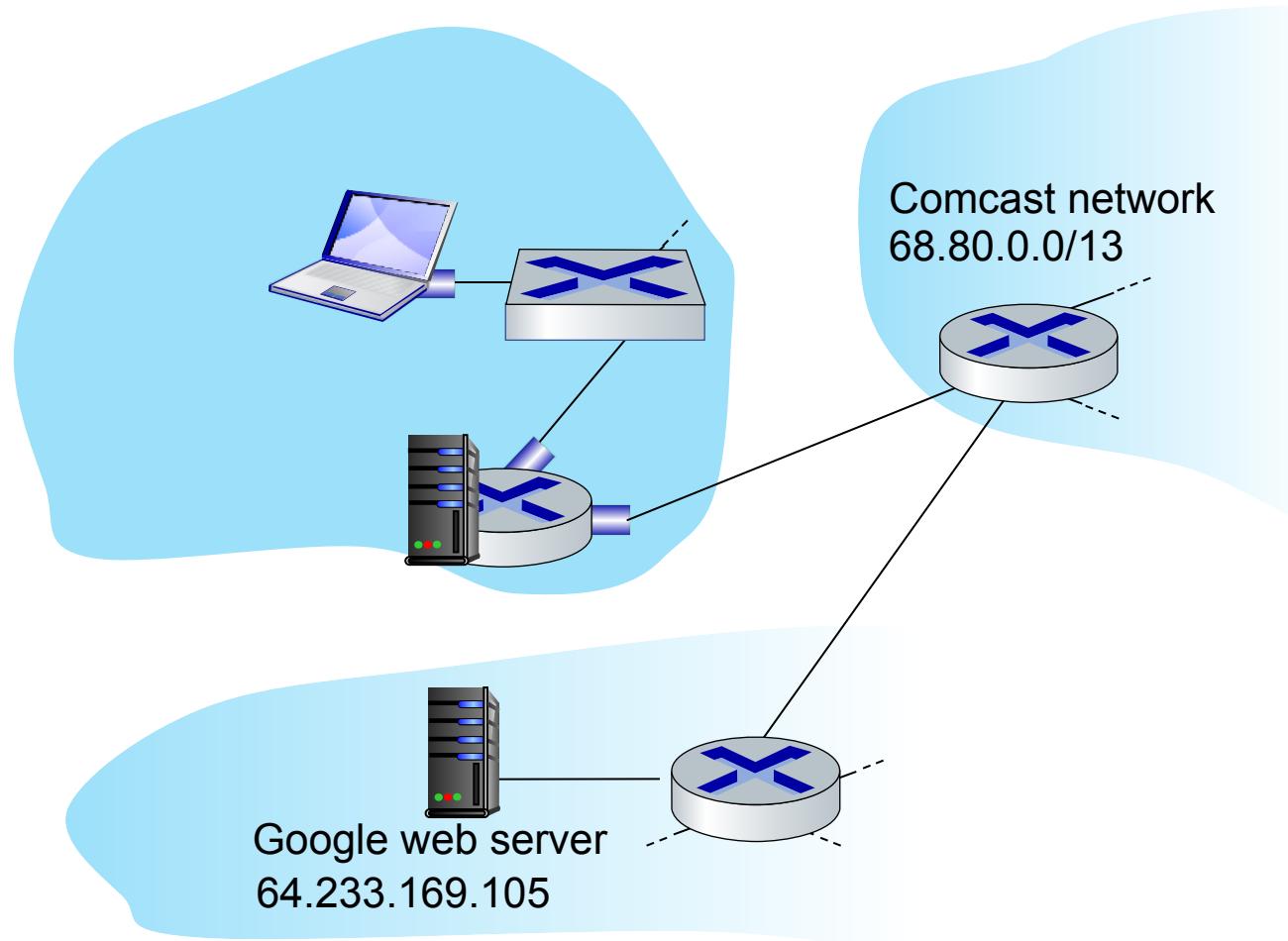
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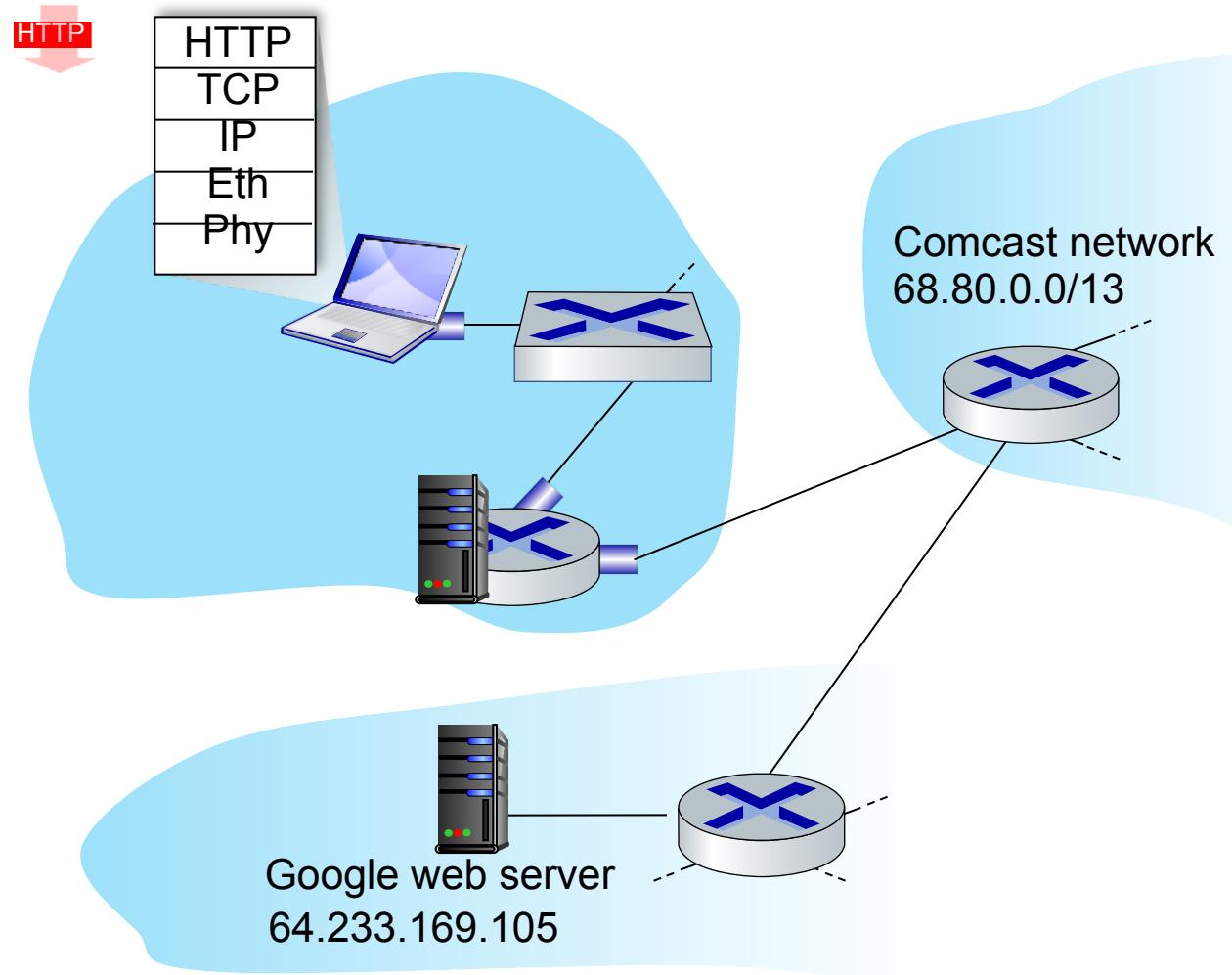
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- demuxed to DNS
- DNS replies to client with IP address of www.google.com

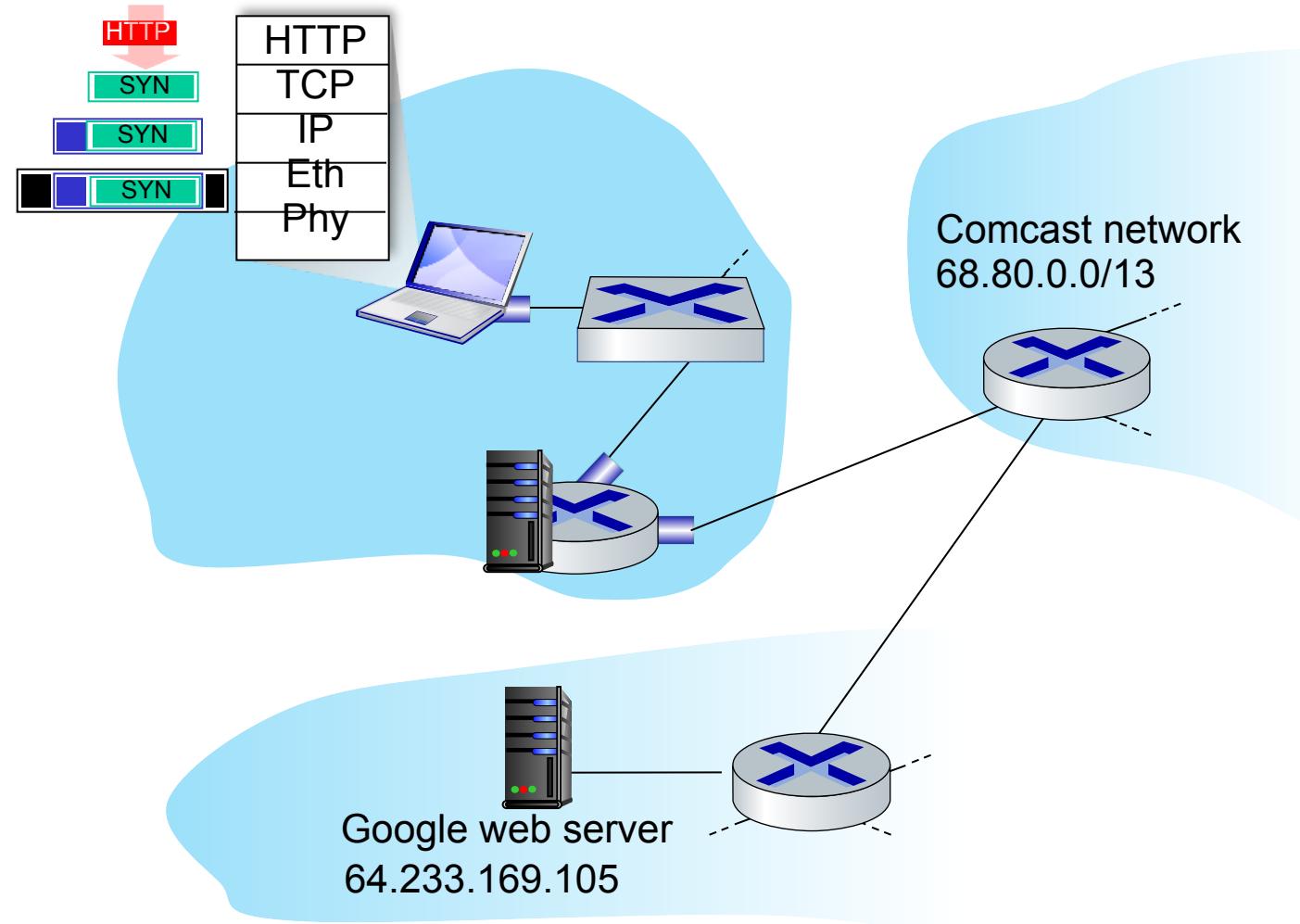
A day in the life...TCP connection carrying HTTP



A day in the life...TCP connection carrying HTTP

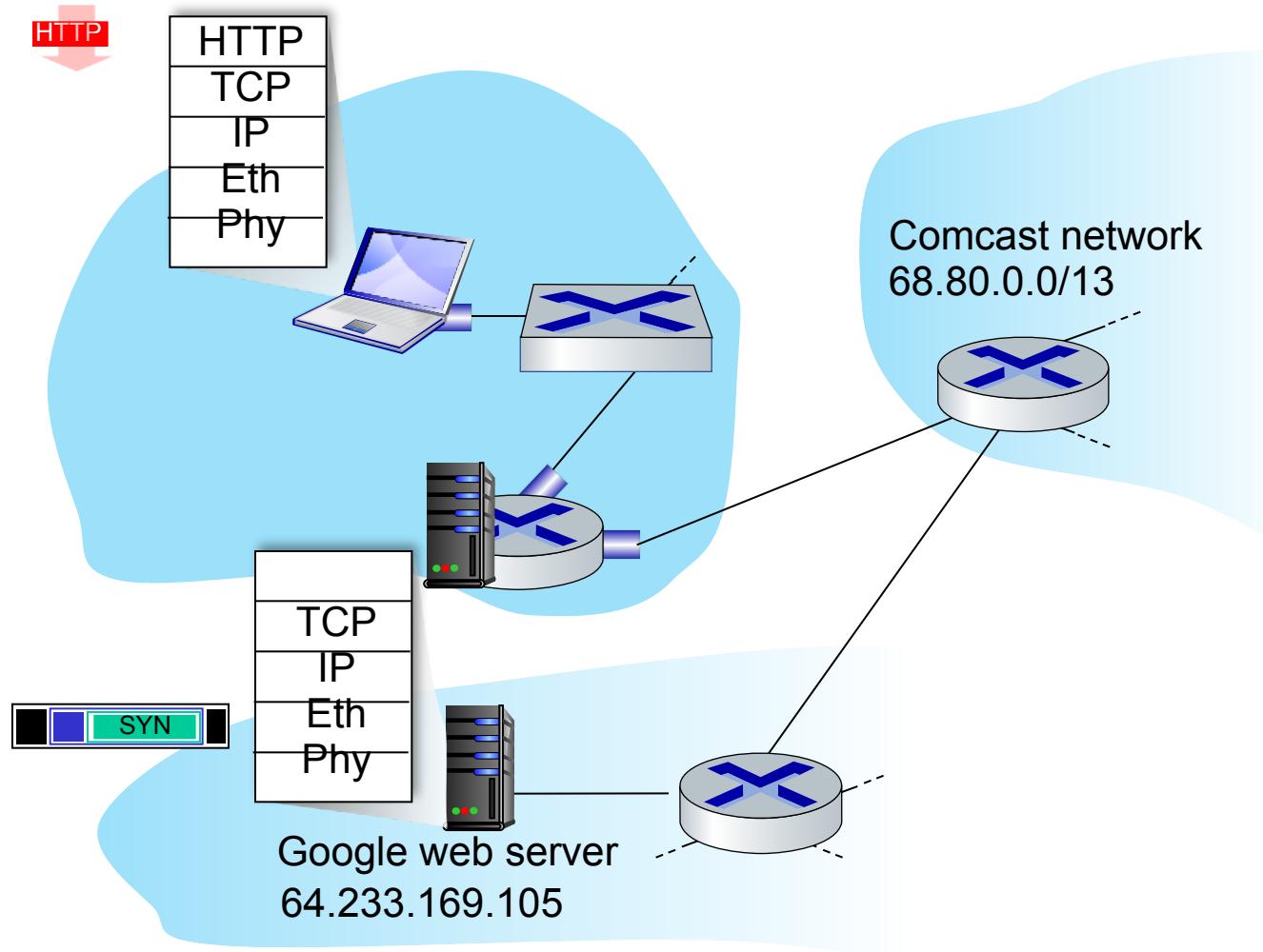


A day in the life...TCP connection carrying HTTP



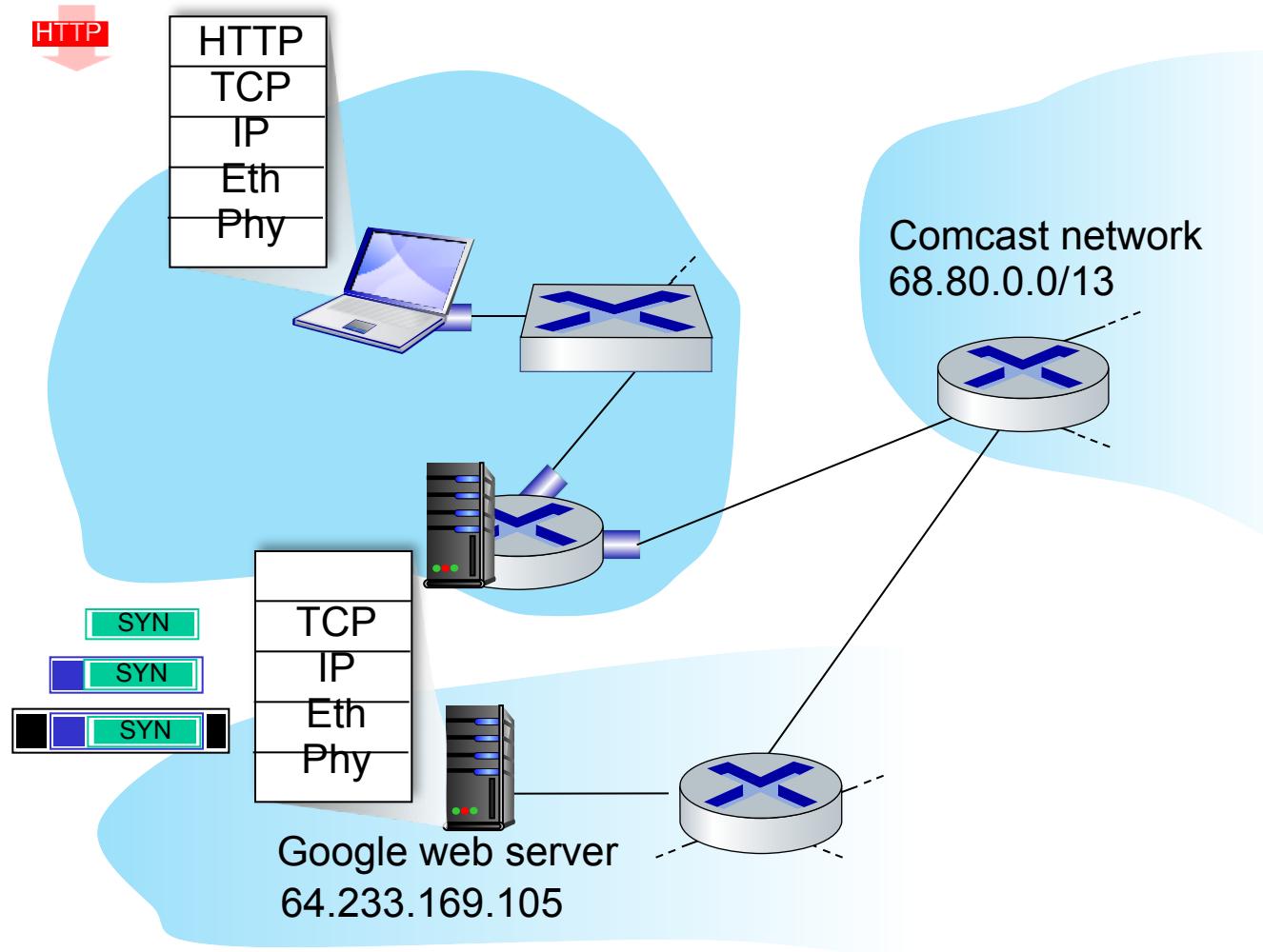
- to send HTTP request, client first opens **TCP socket** to web server

A day in the life...TCP connection carrying HTTP



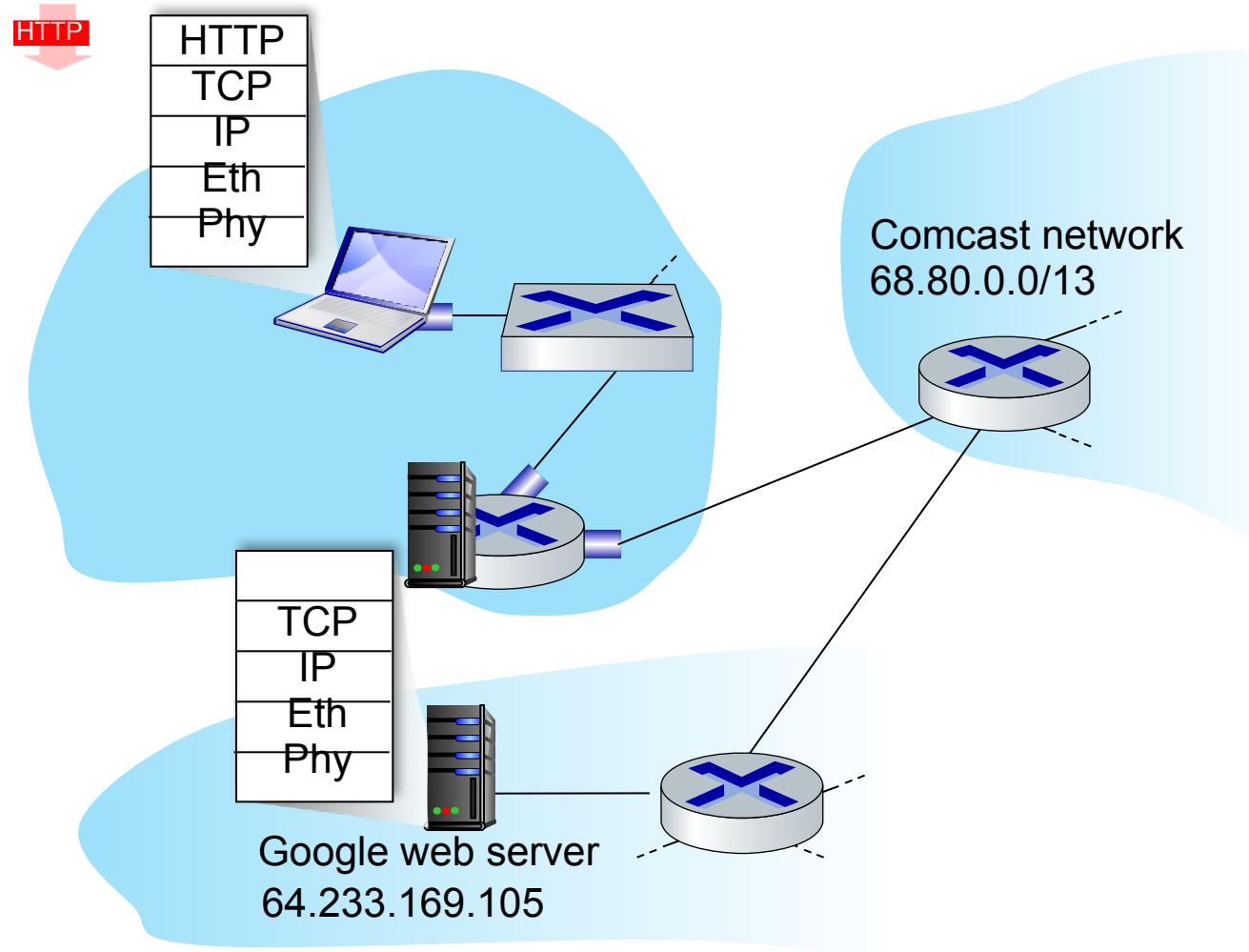
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- **TCP SYN segment** (step 1 in TCP 3-way handshake) inter-domain routed to web server

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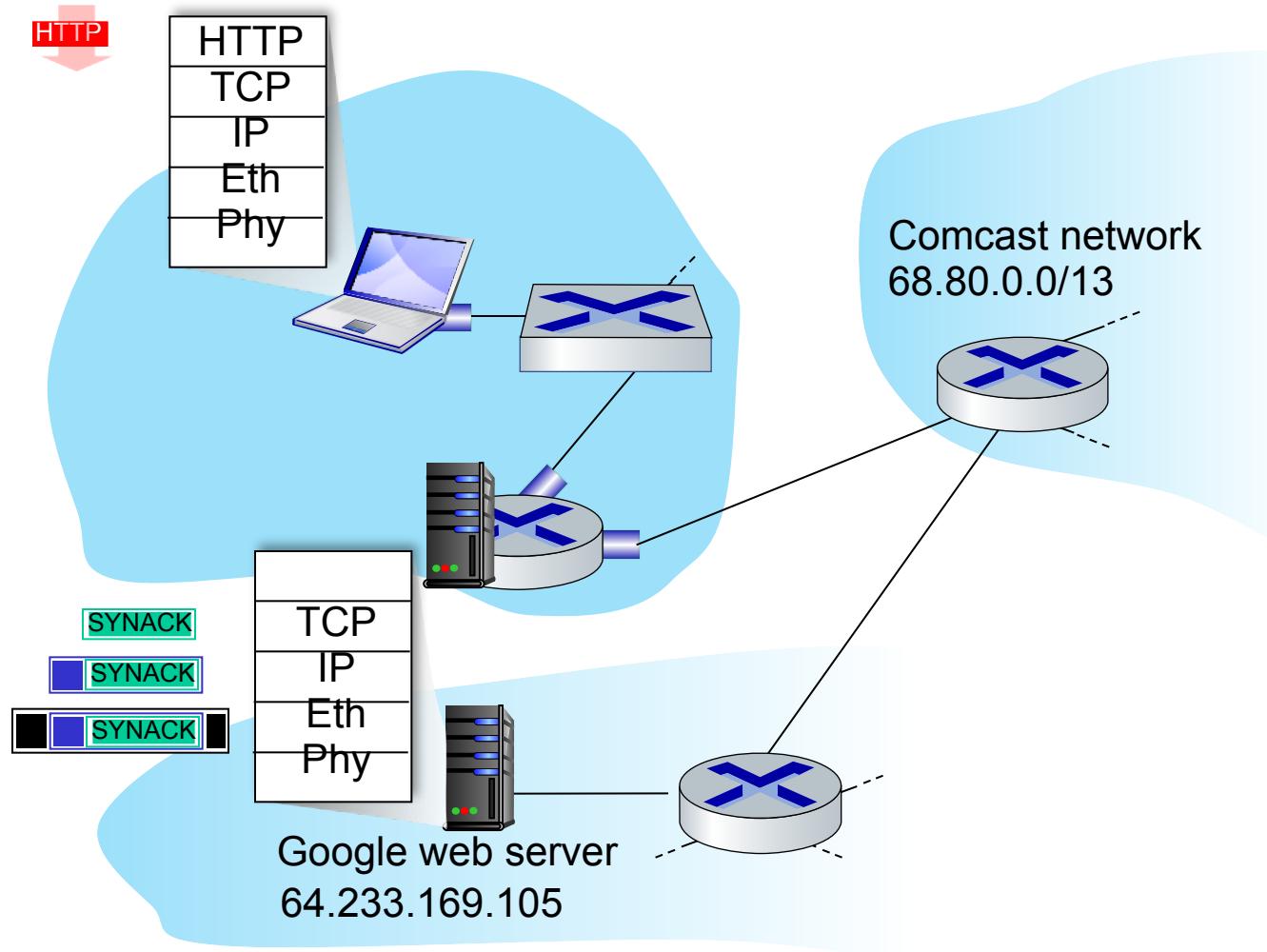
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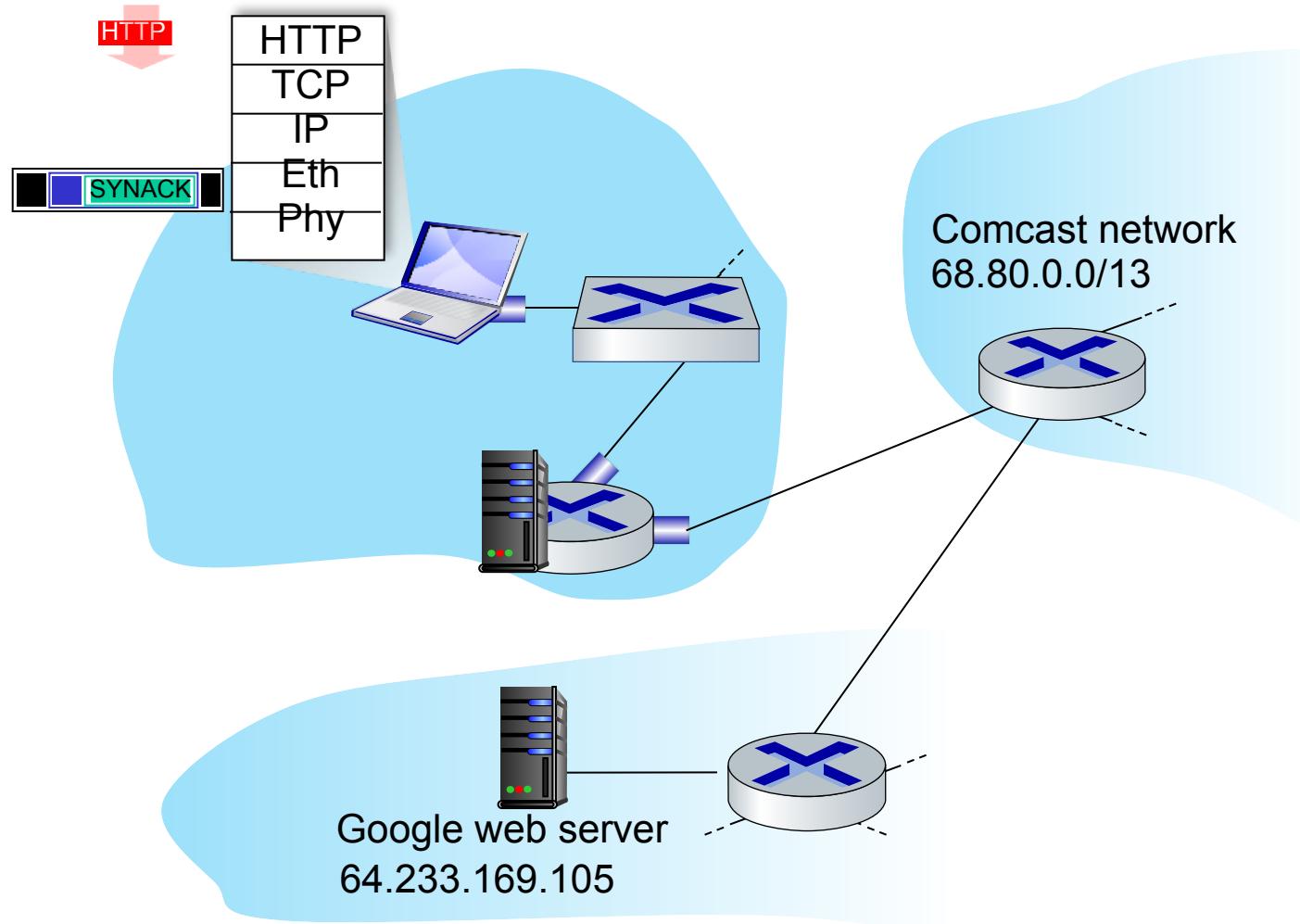
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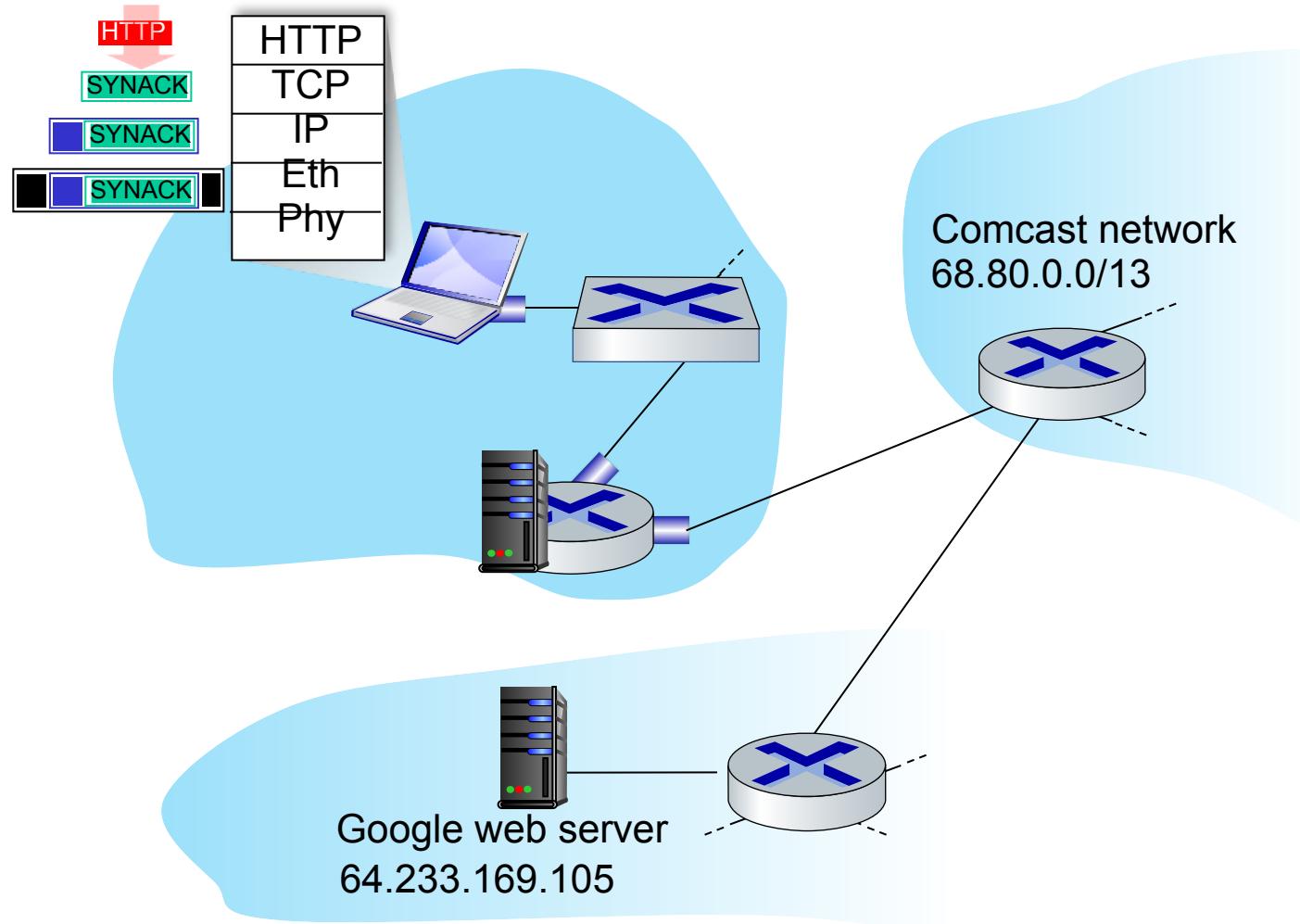
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- web server responds with **TCP SYNACK** (step 2 in TCP 3-way handshake)

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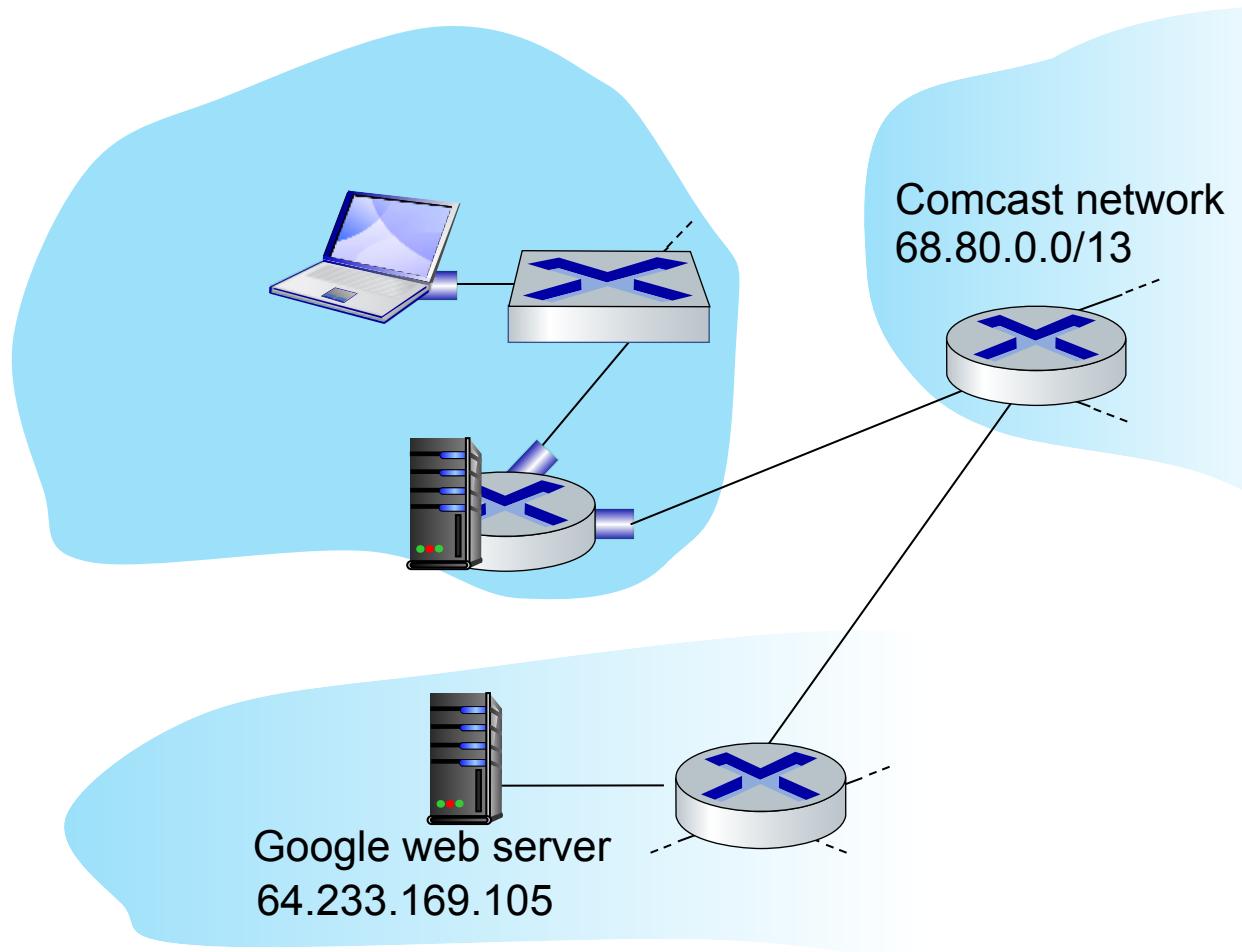
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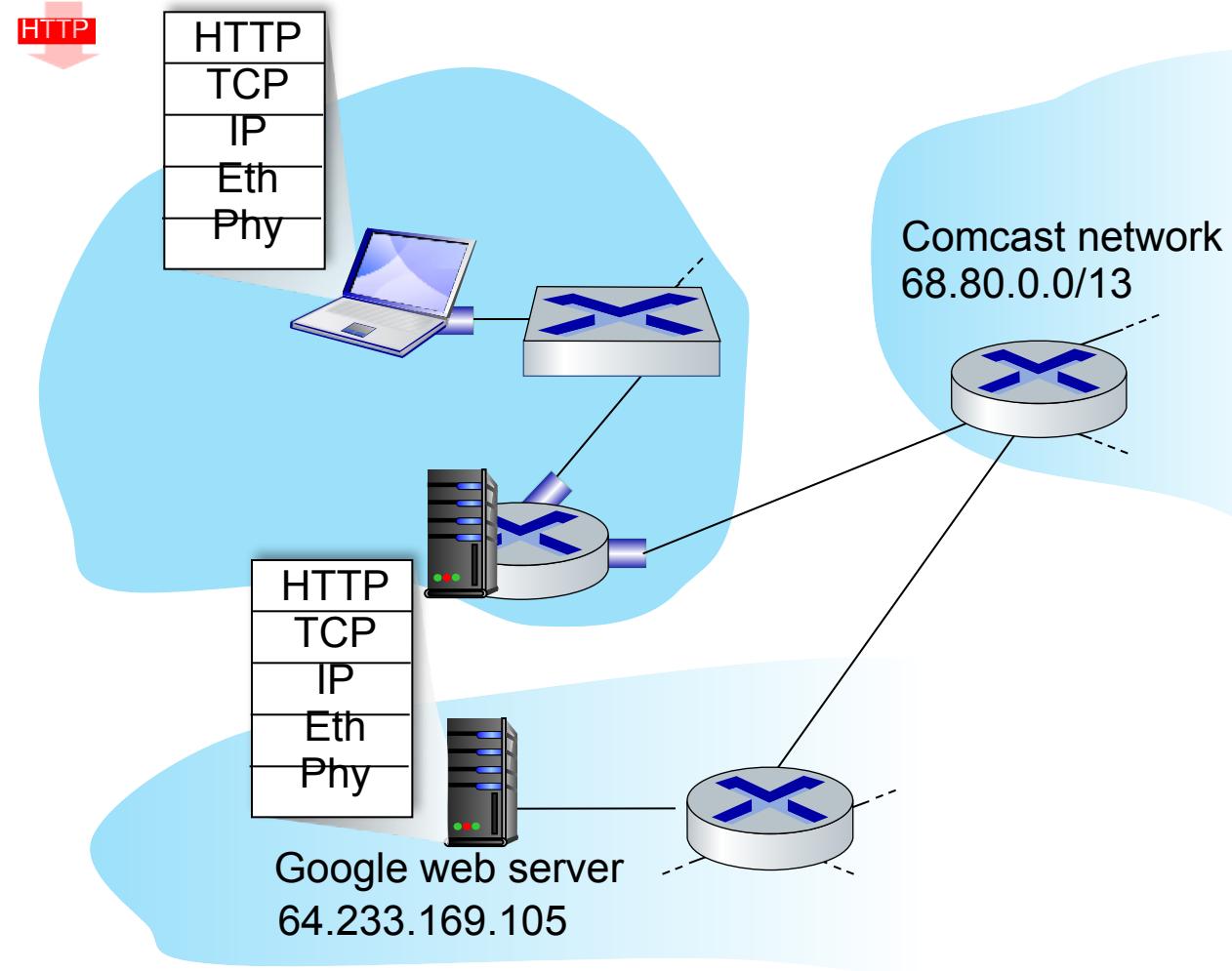


- to send HTTP request, client first opens **TCP socket** to web server
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- web server responds with **TCP SYNACK** (step 2 in TCP 3-way handshake)
- **TCP connection established!**

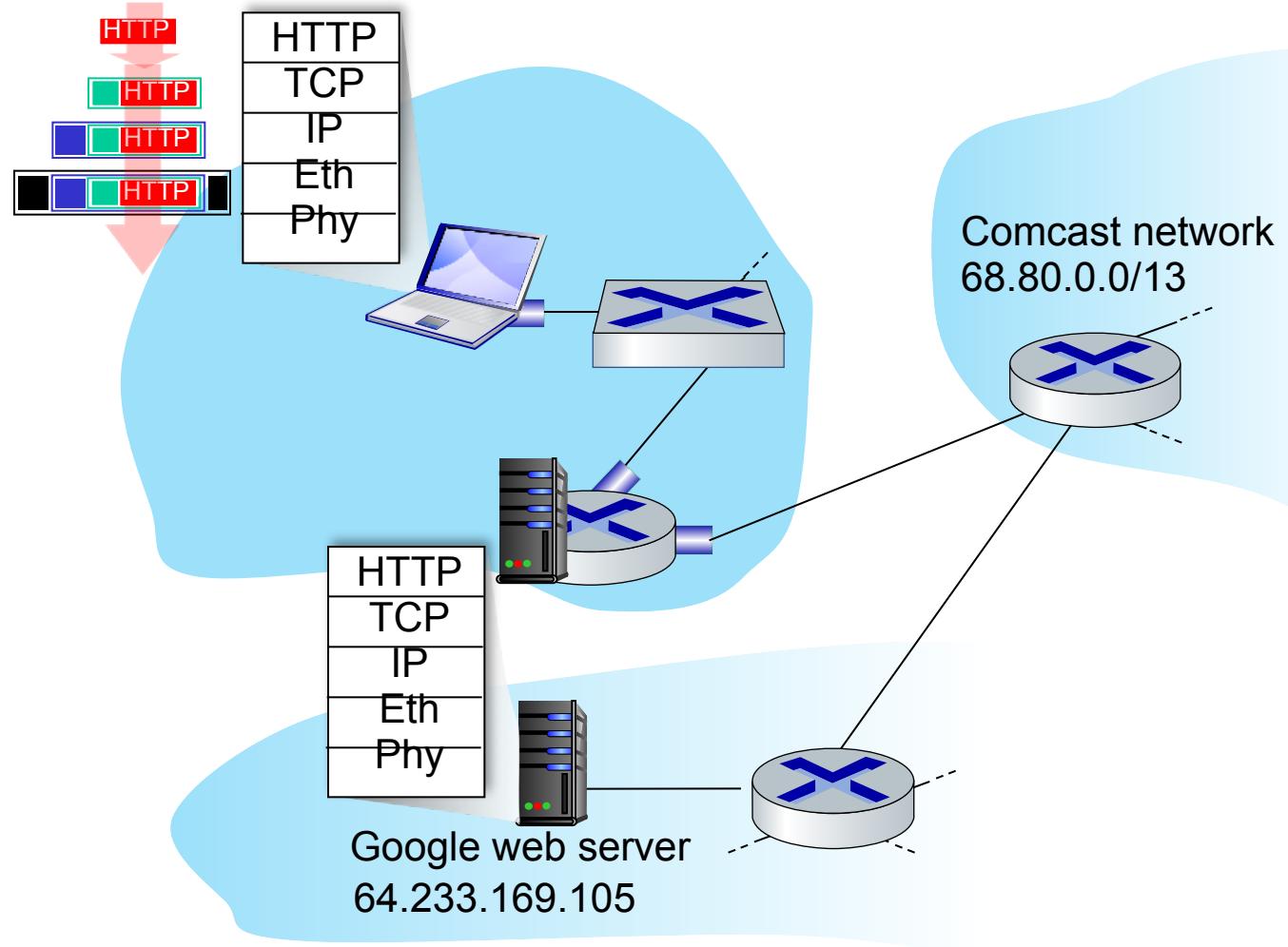
A day in the life... HTTP request/reply



A day in the life... HTTP request/reply

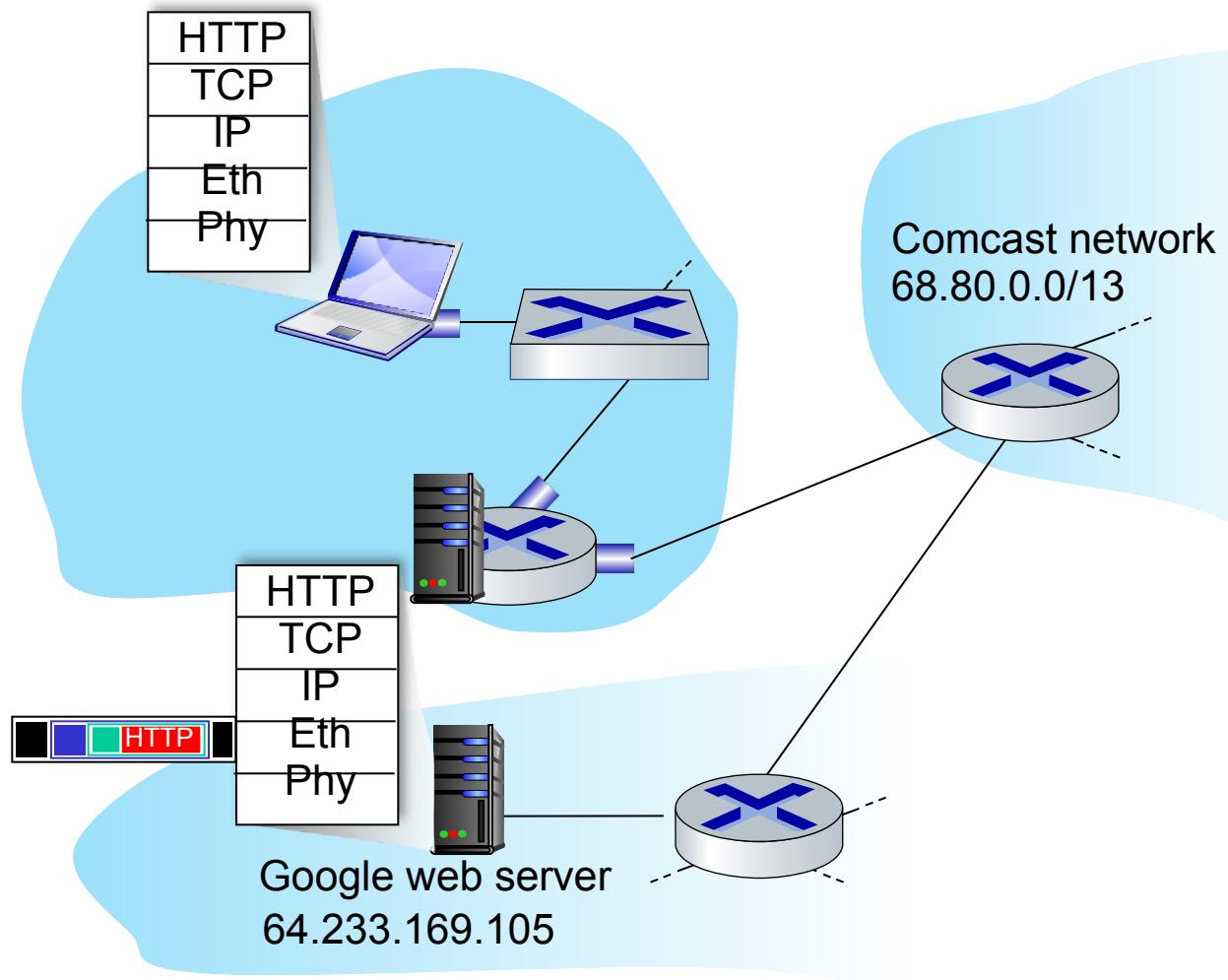


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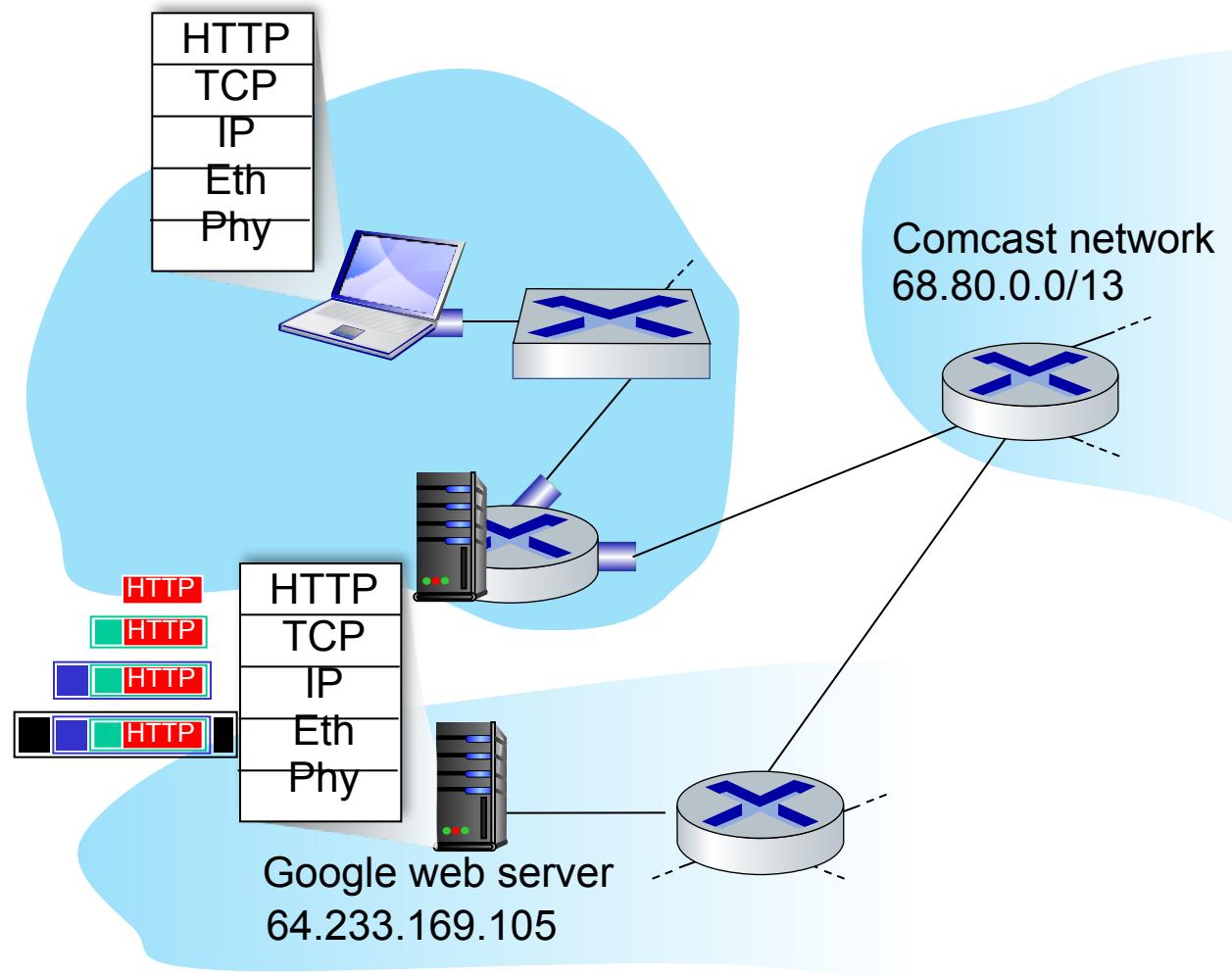
- **HTTP request sent into TCP socket**

A day in the life... HTTP request/reply



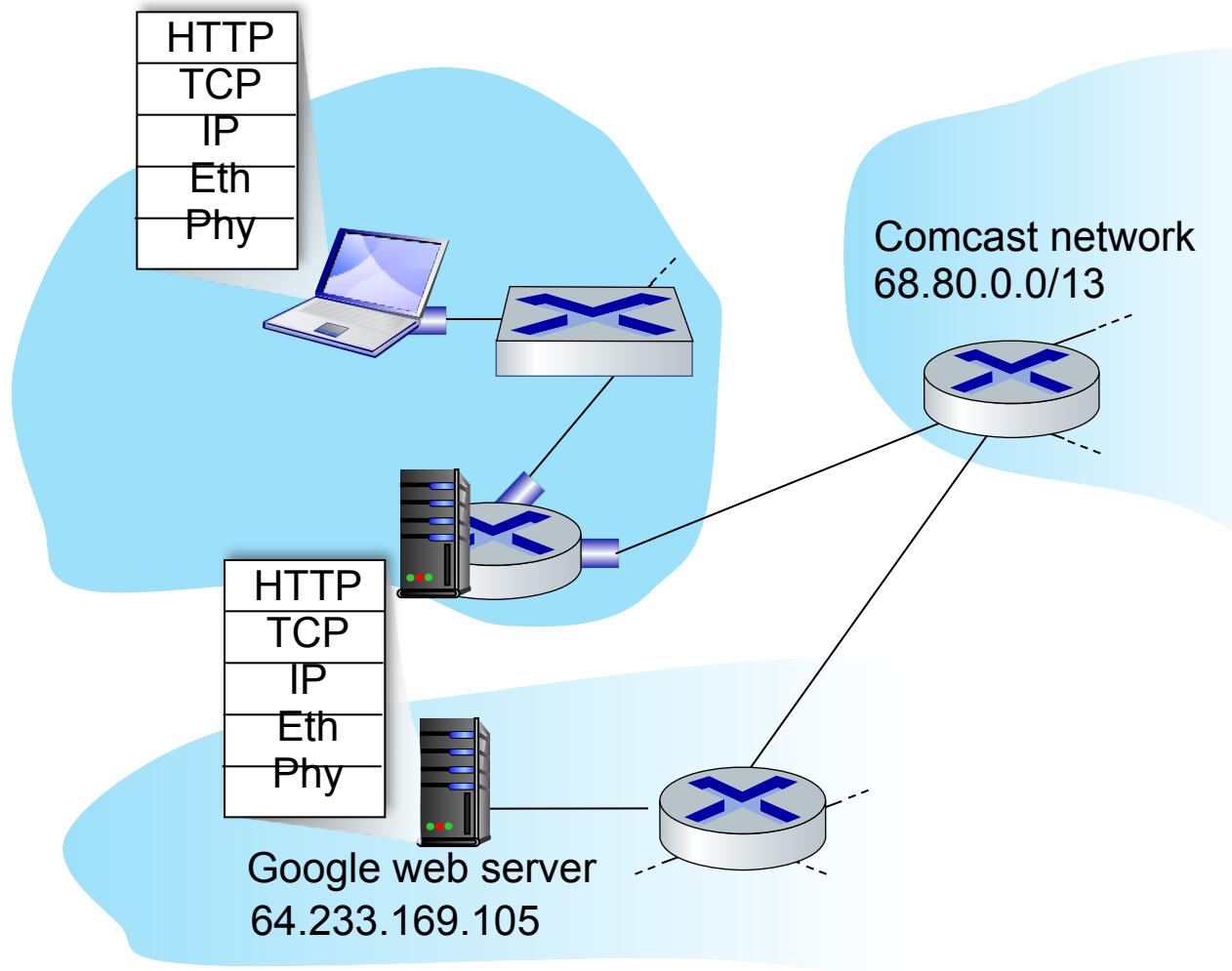
- **HTTP request** sent into TCP socket
- IP datagram containing HTTP request routed to www.google.com

A day in the life... HTTP request/reply



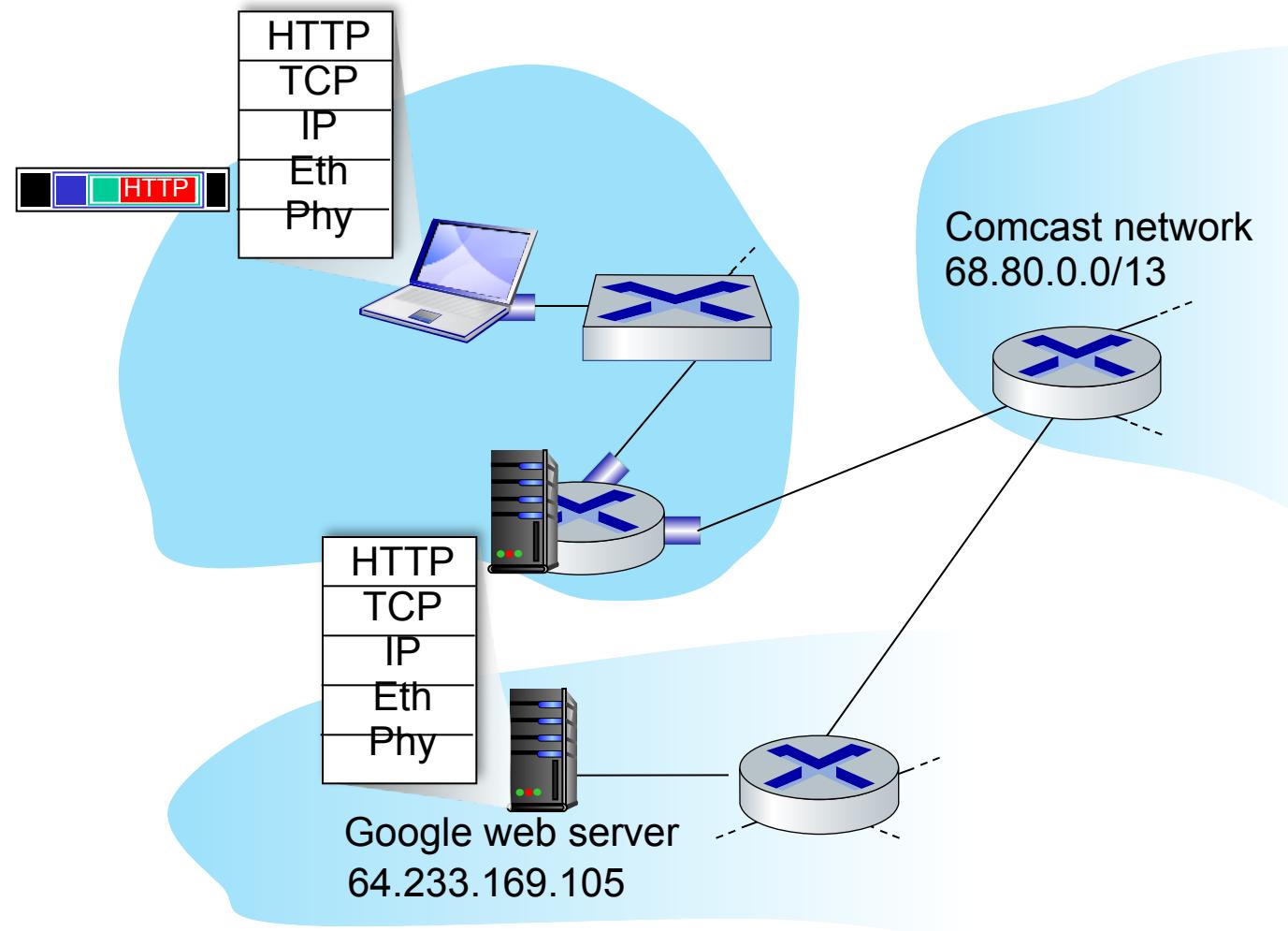
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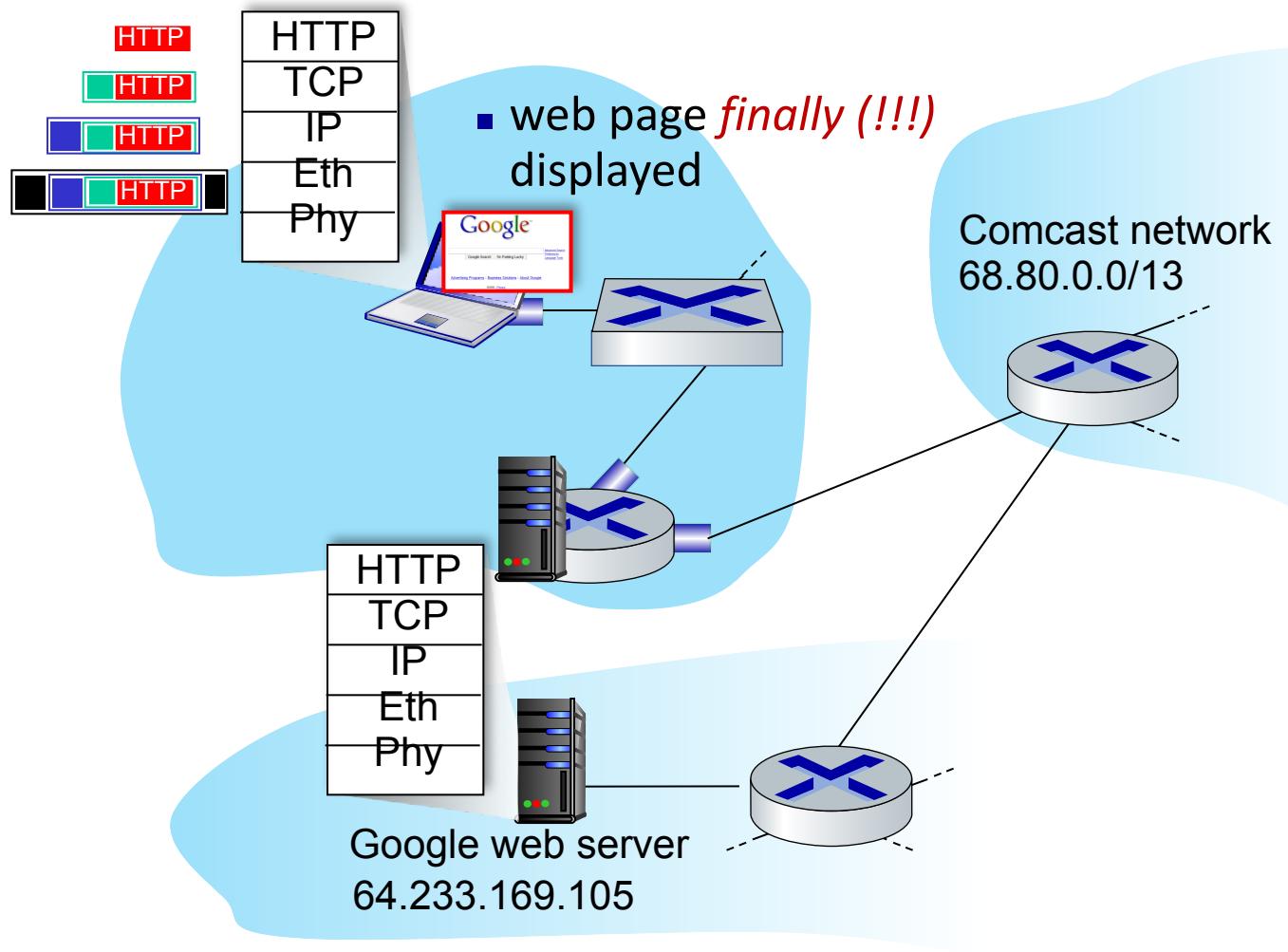
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Chapter 5: done!

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
- datacenter networking
- a day in the life of a web request